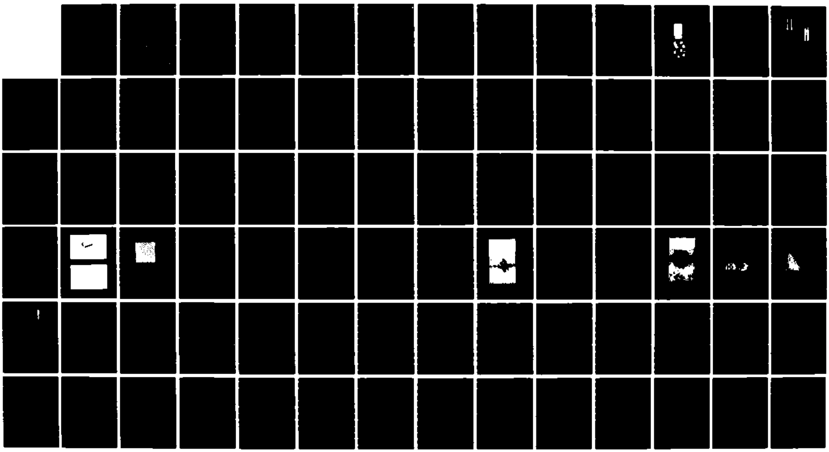
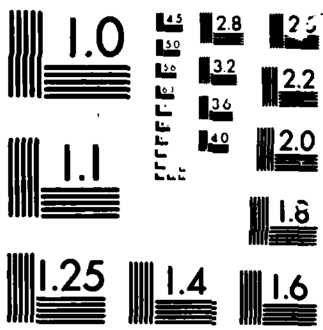
AD-A167 060 MULTIAPERTURE OPTICS(U) FLORIDA UNIV GAINESVILLE DEPT OF NUCLEAR ENGINEERING SCIENCES R T SCHNEIDER 01 MAR 86 AFOSR-TR-86-0233 AFOSR-84-0304 1/1

UNCLASSIFIED F/G 20/6 NL





MICROCOP CHART

AFOSR-TR- 86-0233

AD-A167 060

DTIC FILE COPY

FINAL TECHNICAL REPORT

ON

MULTIAPERTURE OPTICS

BY

RICHARD T. SCHNEIDER

CONTRACT

AFOSR-84-0304

REPORTING PERIOD

9-15-84 THROUGH 1-14-86

DEPARTMENT OF NUCLEAR ENGINEERING SCIENCES

College of Engineering

University of Florida

Gainesville

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

AD-A 167060

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	Unclassified
1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY	
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
3. DISTRIBUTION/AVAILABILITY OF REPORT	Approved for public release; distribution unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	
5. MONITORING ORGANIZATION REPORT NUMBER(S)	AFOSR-TR- 86-0233
6a. NAME OF PERFORMING ORGANIZATION	University of Florida
6b. OFFICE SYMBOL (If applicable)	NES
7a. NAME OF MONITORING ORGANIZATION	AFOSR
6c. ADDRESS (City, State and ZIP Code)	Gainesville, Florida 32611
7b. ADDRESS (City, State and ZIP Code)	Bolling AFB, D.C. 20332
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	AFOSR
8b. OFFICE SYMBOL (If applicable)	NE
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	AFOSR-84-0304
8c. ADDRESS (City, State and ZIP Code)	Bolling AFB, D.C. 20332

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61102F	2305	B4	

11. TITLE (Include Security Classification)	MULTIAPERTURE OPTICS (unclassified)
12. PERSONAL AUTHOR(S)	Richard T. Schneider
13a. TYPE OF REPORT	Final
13b. TIME COVERED	FROM 9-15-84 TO 1/14/86
14. DATE OF REPORT (Yr., Mo., Day)	86-3-1
15. PAGE COUNT	77
16. SUPPLEMENTARY NOTATION	

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The basic principles of Multiaperture Optics are discussed. Based on the results generated under this program, certain applications for multiaperture optics were identified. The main features of an optical instrument based on the multiaperture principle are, that such a sensor will necessarily have to be small, and need to be a mass product. Large scale integration would have to be used to evaluate data collected and perform pattern recognition. It is a necessity to perform these functions in the sensor itself, using parallel input into the circuitry.

An experimental device has been built and tested. It is capable of recognizing simple shapes.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT

UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
LtCol Carter	202-767-4932	AFOSR/NE

DD FORM 1473, 83 APR   EDITION OF 1 JAN 73 IS OBSOLETE.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

FINAL TECHNICAL REPORT

ON

MULTIAPERTURE OPTICS

by

Richard T. Schneider

CONTRACT
AFOSR-84-0304

Reporting Period

9-15-84 through 1-14-86

University of Florida
Gainesville, Florida

PART I

1. INTRODUCTION

This report describes the effort carried out under Contract No. AFOSR-84-0304 (9-15-84 through 1-14-86).

The Chapters 1-5 deal with the basics of Multiaperture Optics (MAO) while Chapters 6-10 describe the experiments performed and the results obtained during this effort.

The design of multiaperture devices has been advanced to a state where it became possible to build a working model capable of acquiring simple shapes as well as recognizing them.

2. INSECT VISION AS A MODEL

a. Introductory Remarks

The development of optical instruments, at least the photographic camera, was undoubtedly inspired by the then existing knowledge of the anatomy of the human eye. Therefore it is probably appropriate to try this approach again for the development of a new type of optical instrument based on the design of the insect eye.

While the anatomy of the eye was known, this did not mean that the functioning of the eye was indeed completely understood at that time. The same is true for the insect eye. The anatomy of it is well known. However, the function of each of the components of the eye is still subject to controversy. It is not the objective of this research effort to get involved in this controversy. Rather a different approach will be chosen here. We will take the optical components and ask what a designer would do with it to obtain a functional instrument regardless of the fact that there is the possibility that nature may have used these components in a different way.

Therefore, in the following we give a brief description of the anatomy of the insect eye and ~~in the next chapter we will design~~ an instrument using similar components.

There are basically two types of insect eyes, the apposition eye and the superposition eye.

In general it is automatically assumed by the workers in the field that the insect eye produces an image which is handed over to the brain as such. In contrast to this we believe that the eye is a digital data gathering device, which performs recognition of objects in the eye itself and transmits only the results of the recognition

process to the brain. Nevertheless the mosaic theory of insect eyes states that each eyelet (ommatidium) contributes one point to the image the insect conceives. Depending on the species, there can be up to 20,000 ommatidia in an eye. In this case, the image would be made up of 20,000 pixels, which would make an image of only moderate quality. However, there are indications obtained through behavioral research that the insect, indeed, sees quite well. Therefore, our suspicion is that one ommatidium does more than collect only one point of the image.

b. The Apposition Eye

Figure 1 is a simplified diagram of the structure of an apposition eye. The main optical elements consist of two lenses (the corneal lens and the crystalline cone) and a bundle of 7 to 8 detectors (the rhabdom). We like to suggest that the cone is a light horn*), while the corneal lens is a field lens. And, indeed, in Reference 1 it is claimed that the crystalline cone is almost identical to the ideal concentrator (light horn). However this assumes that the refractive index is a uniform n = 1.54, which is actually not the case for most eyes. Rather, the index is changing in the radial direction. However, this should not modify the function of the light horn too much. Light, which enters the light horn under an extreme angle is reflected back out of the entrance aperture, meaning this device has a limited acceptance angle. Therefore, the lens in front of the light horn has to be considered as a field lens, which regulates the entrance angle and consequently the FOV of the individual eyelet.

The rhabdom, which is a long hose-like structure, contains 7-8 individual detectors (the rhabdomeres). They are either separated or

*) A light horn (Raleigh's light horn) is a nonimaging optical component. It is funnel shaped and concentrates light by regular or total reflection.

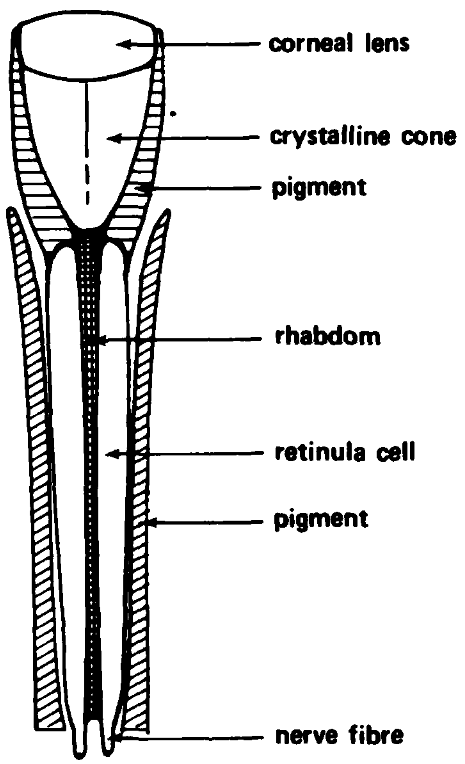


Figure 1. The Apposition Eye

fused together as indicated in Figure 2. Most apposition eyes have fused rhabdoms. In general an oblique skewed ray entering any cylinder with reflecting walls will spiral down this cylinder. The rhabdom is such a cylinder filled with pie-shaped segments (the rhabdomeres). In this case, indications are that each rhabdomere has a different color sensitivity and/or serves as a color filter for its neighbors.

The fine structure of these rhabdomeres consists of rows of small tubes, typically 1 μm in diameter. Layers, consisting of several rows, are alternatingly oriented, 90° to each other (see Figure 3). These tubes are called microvilli. The light is kept inside the rhabdom by total reflection on the internal walls of this hose-like structure. The absorption of the photon occurs in one of these microvillis, which are the organs which convert the light signal into an electric signal (or rather an electro-chemical signal).

Each ommatidium is surrounded by pigment cells. This pigment serves as optical insulation between neighboring ommatidia.

c. The Superposition Eye

This type of eye, as can be seen in Figure 4, is similar to the apposition eye. The main difference is a piece of fiber optics (the cytoplasmic filament) which is inserted between the crystalline cone and the rhabdom. At low light levels there is little or no optical insulation between the individual cytoplasmic filaments. However, if high light levels are present a pigment layer is moved between each filament as indicated in Figure 4.

For the case when there is no pigment between the filaments, the theory states that the image which is formed by each lens spreads out over more than one rhabdom, in fact, a large number of rhabdoms. This is, supposedly, true for each lens and, therefore, many images are

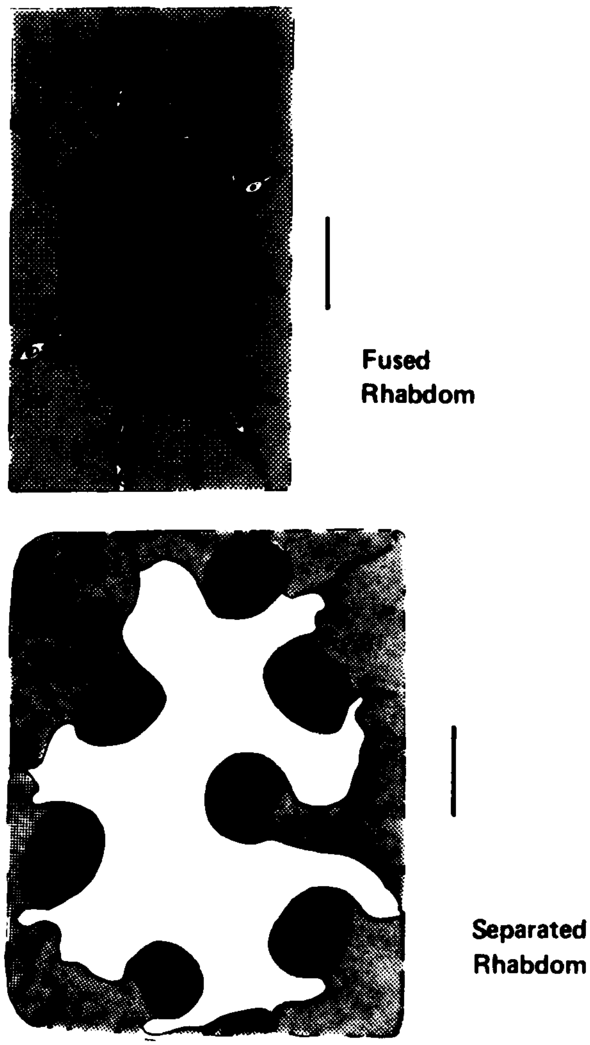


Figure 2. Rhabdoms

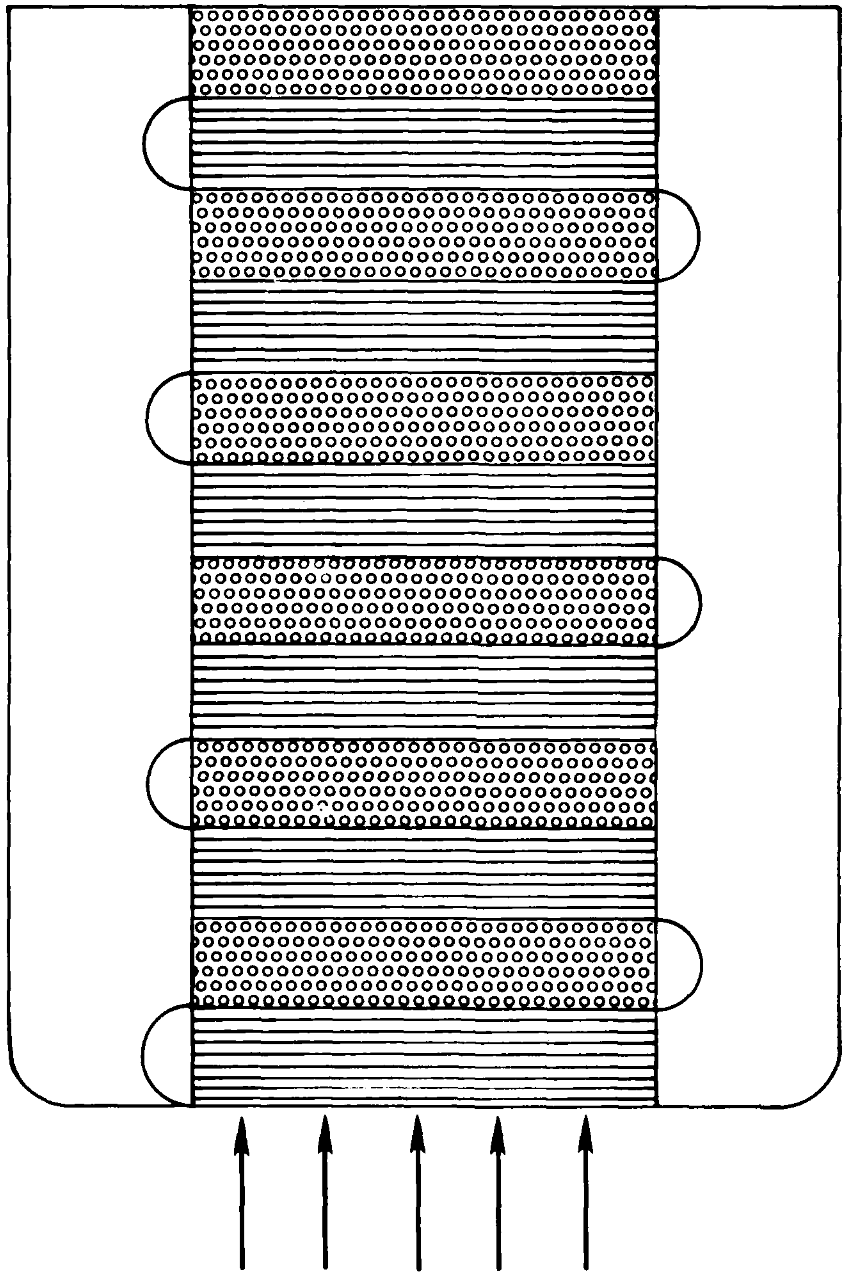


Figure 3. Structure of Rhabdom, Showing Microvilli

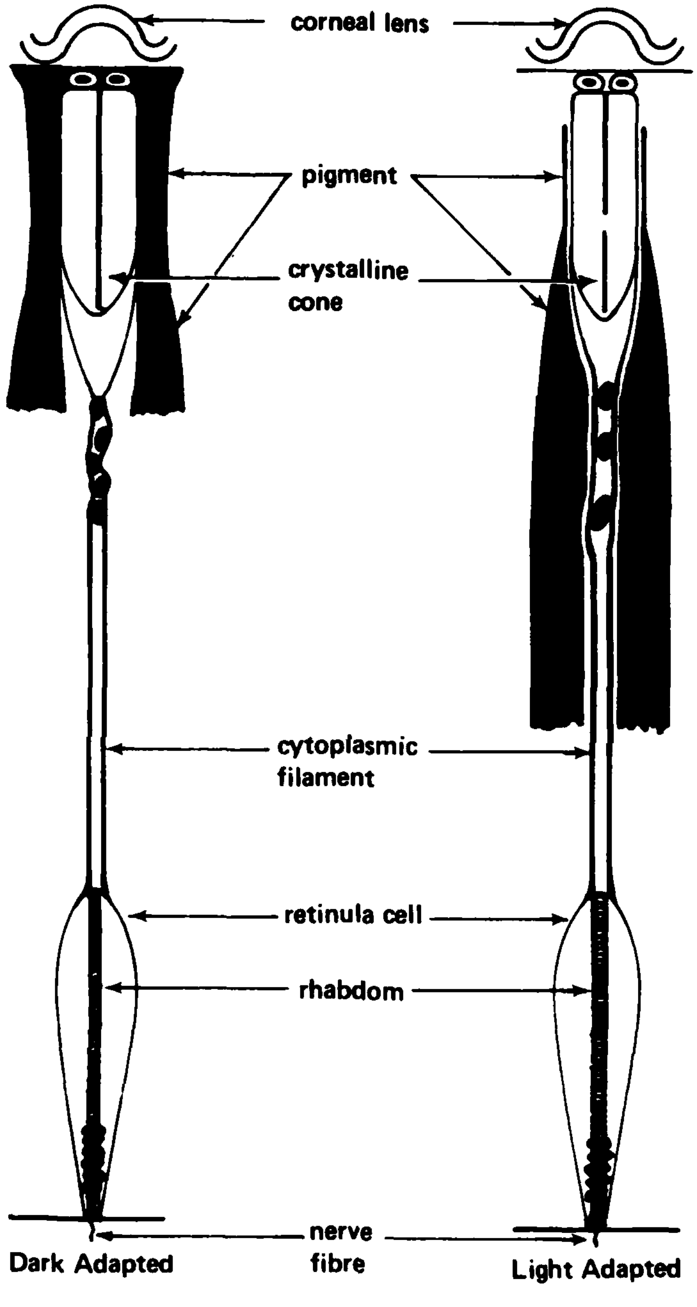


Figure 4. The Superposition Eye

superimposed. If properly aligned, they should form one superposition image.

Since not all entomologists subscribe to this theory, the superposition eye is sometimes also called "clear zone eye," referring to the clear space between the crystalline cone and the rhabdom.

For low light levels, where there is no optical insulation between the individual eyelets, a superposition image is supposedly obtained, while at high light levels the superposition eye would be converted into an apposition eye, since pigment is moved between the individual eyelets, which makes the formation of a superposition image impossible.

The fact that the superposition eye turns into an apposition eye at high light levels makes one wonder about the validity of the theory of the superposition image. It should be noted that in order to convert back to the superposition eye not only does the pigment need to be withdrawn, but also the refractive index of the filament has to be made equal to the index of the surrounding liquid to allow formation of a superposition image.

From the standpoint of a designer, one would use the cytoplasmic filament as a device which regulates the FOV of the individual eyelet and above all regulates the amount of light (intensity) which is allowed to strike the rhabdom. Since the light spirals down the inside of the cytoplasmic filament by total reflection, intensity control can be accomplished by "frustrated total reflection." This implies that the light travels inside the filament at all light levels and at all times, and is modified (reduced in intensity) when pigment is present in the liquid adjacent to the wall of the filament. In this case less

than 100% of the light is reflected by total reflection. The superposition eye is usually associated with a separated rhabdom (detector array) as shown in Figure 2 (lower half). The detectors form a ring containing six detectors which surround a central detector number 7 (or to be precise 7 and 8 which are fused together). We would like to assume that the center detector sees only that part of the FOV, which is non-overlapping with the FOV of the neighboring eyelet while the ring of six detectors detect the overlapping parts of the FOV. If the filament serves as a waveguide in both cases, high light level and low light level, the introduction of pigment around the cytoplasmic filament would only change (by frustrated total reflection) the intensity carried in the waveguide but not change the method of data evaluation.

From the point of view of a designer, a superposition image will not offer any advantage over an apposition image. The resolution of the image is determined by the diameter of the optical system of an individual eyelet, therefore, it has to be the same as for the apposition image. The number of detectors available to probe the image is also the same in both cases. The retina in the insect eye is convex (as opposed to the concave retina of the human eye), therefore, a large image would run out of focus at the edges quite soon. Therefore there is really no good reason to accept the additional complication of aligning the many images for superposition. Maybe nature does this anyway, but for our optical instrument the superposition image is not an acceptable option.

There are three layers of nerve nets underlaying the insect eye structure (as compared to only two in the case of the human eye) and relatively few nerves connected to the brain. Based on this, we

suggest that the pattern recognition is performed in these nerve nets, and only the result of the pattern recognition is forwarded to the brain.

There is experimental evidence that both eyes communicate with each other. E.g., if only one ommatidium in one eye is illuminated, the brain checks if the corresponding ommatidium in the other eye is also illuminated. It can do this despite the fact that only a few nerves are connected to the brain, meaning that not every ommatidium has its own connection to the brain. In order to select a certain ommatidium in the other eye, the incoming signal must be coded with respect to the position of the illuminated ommatidium. This is a strong indication that substantial processing is performed in the eye itself.

For this reason we suspect that the insect eye is not a camera delivering an image to the brain, but a pattern recognition device delivering a signal to the brain, which announces the kind and location of an identified object. This is the same goal we see for the MAO system. It should not be thought of as a TV camera, providing an image for a human observer, but as a device which recognizes an object and announces its location.

3. THE OPTICS OF MULTIAPERTURE OPTICS SYSTEMS

a. Introductory Remarks - Why Multiaperture Optics?

The resolving power of an optical system is determined by the lens diameter. Going to small lenses means severe penalty in resolving power. Obviously there have to be other benefits to justify the use of Multiaperture Optics (MAO). It is safe to assume that such benefits exist, otherwise nature would not have been able to evolve MAO-eyes against what would otherwise be superior competition. What is not so obvious is the answer to the question, are these benefits of any value for the optical instrument we want to build? E.g., it could be that MAO is only good for close distances--less than the one focal length required for a one-lens system. This would make sense for an insect, but may restrict possible applications for our optical instrument severely. Therefore, we will devote this chapter to discussing the possible answers to this question.

b. Advantages of MAO

The more obvious advantages are

1. Small size
2. Large FOV
3. No focusing required
4. Optical Preprocessing

while the obvious disadvantages are

1. Poor resolution
2. One individual detector is served by a smaller aperture than in the case of single lens optics.

The consequences of reduced aperture are illustrated in Fig. 5. As can be seen in Fig. 5a detector X is served by the large aperture lens, while detector Y is also served by the same aperture, although under a slightly different angle. In the case of MAO, as can be seen

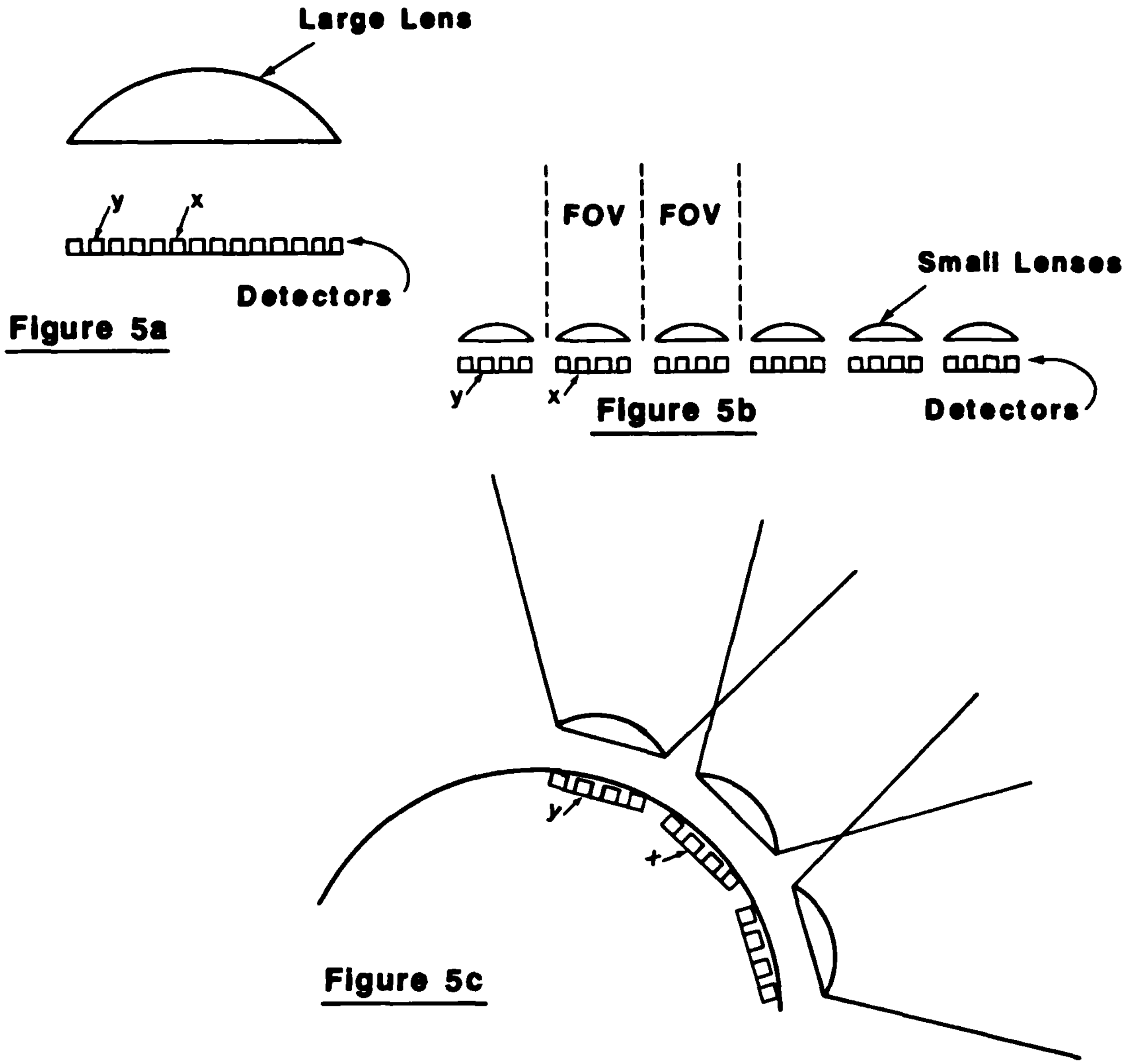


Figure 5. Comparison Single Lens Optics vs. MAO

in Fig. 5b, the aperture which serves detector X is much smaller and detector Y is served by the neighboring optical system. It looks as if, in the case of single lens optics, the lens is used repeatedly, while in the case of MAO the light horns are used only once. If one were to use a flat array as shown in Fig. 5b one would intercept considerably less photon flux per detector than is the case in single lens optics in Fig 5a. Or, in other words, for a given FOV one would intercept the same photon flux, but would distribute it over a larger number of detectors. If it is not a flat array but a convex one, as shown in Fig. 5c, depending on the FOV overlap, more than one eyelet covers FOV now, and FOV could not be covered by the single lens. Nevertheless, one can see that if there is an intensity problem MAO may be at a disadvantage. However, if there is sufficient light the distribution over more detectors may be advantageous.

The question of close distances and multiple service of a single lens can be nicely illustrated with an example depicting a well-known device--the faceplate. Figure 6 shows an oscilloscope camera. If a single lens is used, the best f-number, which can be achieved with reasonable effort, is around f/1.5, which would correspond to an acceptance angle u = 34°. If a faceplate were to be used, this angle could be considerably larger. For simplicity let's assume the faceplate consists of cylindrical tubes having reflecting interior walls. In this case, any ray falling into a cone with u < 180° will be reflected and delivered to the detector. Therefore, despite the fact that the entrance aperature of the cylinder is so much smaller than the one in the case of single aperature optics, the detector actually receives more light in the MAO case. As can be easily seen, this advantage of MAO disappears if the light source is moved away to a large distance.

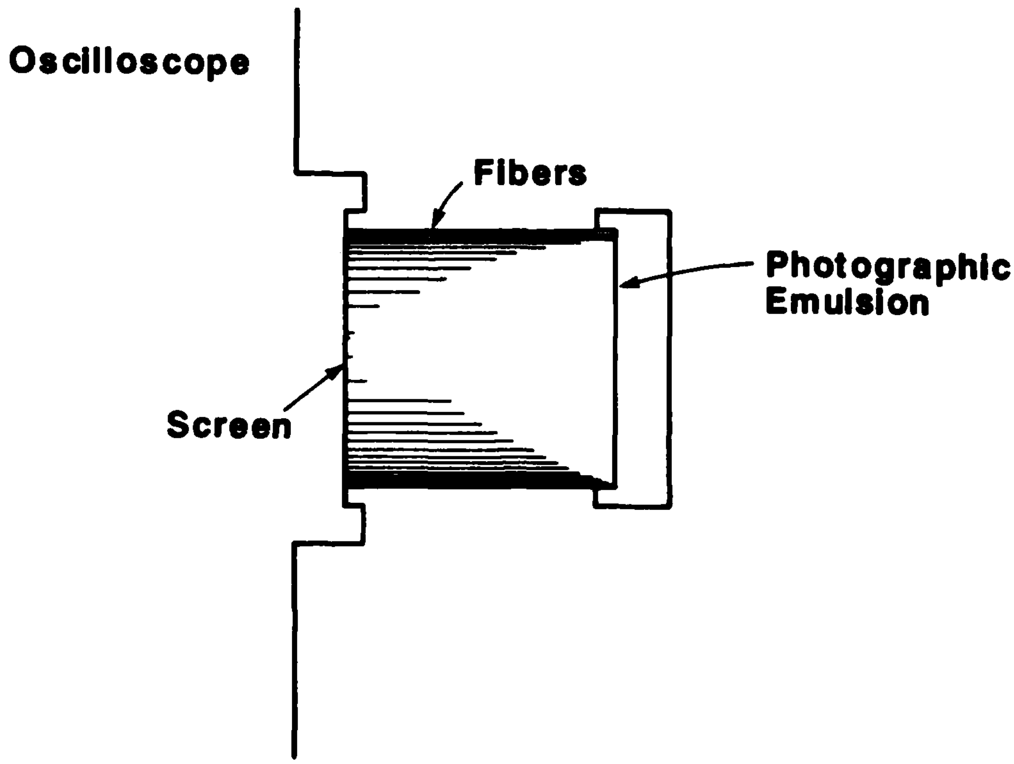


Figure 6. Faceplate Camera

From this superficial listing of advantages and disadvantages one can already see what applications may be appropriate for MAO. Without any further discussions we can state that any application which can be accomplished by a roving TV camera should not be attempted with MAO, since the performance of MAO has to be necessarily inferior to the performance of the TV camera.

However, if there were a requirement that the camera cannot be larger than a postage stamp, cannot be thicker than 1/8" and has to be an inexpensive mass product, then the TV camera cannot satisfy the requirement and MAO has to be used, inferior performance or not. A small TV camera cannot be used in principle, since focal length and aperture are related through the f-number in the case of single lens optics. Such a relationship does not exist for MAO; for a given focal length the total aperture can be made as large as desired. In our example the 1/8" thickness limits us to a focal length for the TV camera of 1/8" and therefore a single aperture between 1/8" and 1/16". This already puts the TV camera in the MAO regime. Therefore, size is the governing factor and indeed, in nature, only small animals use MAO. One may argue that this is coincidental since the dividing line between MAO and SLO is constituted by the type of skeleton (vertebrate or invertebrate). Maybe the exoskeleton cannot support a large animal, or a large invertebrate animal could not compete because of its inferior eye. Whatever the reason may be, the fact is that only small animals seem to be successful with MAO eyes. Therefore, one main concern here is to find out if MAO is at all useable for far distances.

However, from behavioral research we know that insects find objects by sight, which are reasonably far away. Of course we do not know how well they see in the distance, we only know they can function.

c. The Architecture of a MAO Instrument

For the design of our MAO instrument we will assume that one eyelet collects one pixel of the overall image. This is a design decision and is an option chosen from three possibilities. The rational for rejecting the two other possibilities, namely superposition and fragmented images, are discussed below. A fragmented image is obtained when one eyelet will create a small section of the overall image. (This is in contrast to the apposition image, where one eyelet creates only one pixel).

The superposition image is not attractive for a MAO optical instrument, since the "retina" is convex by necessity; also, the precise alignment of so many lenses to obtain good superposition would be very difficult.

Ruling out the superposition image means one elects optical insulation between the individual eyelets or at least to limit the overlap of FOVs with neighboring eyelet to a few neighbors rather than a large number of neighbors as is the case with the superposition image.

A fragmented image would have to consist of individual small images about the size of the eyelet. If limited overlap with neighboring eyelets would be chosen, then the alignment problem is again a consideration. A reasonable number of detectors would be required in each eyelet (more than the 7 or 8 which are used in the insect eye). This is, of course, doable, however, it would require focusing of each

eyelet, at least initially during the assembly process. Once focused each eyelet could be operated as a fixed focus camera due to the short focal lengths of the individual lenses.

We do not choose the fragmented image option because of the focusing requirement during assembly since we believe the difficulty to guarantee focusing of so many lenses is overwhelming. As pointed out above, the MAO eye has to be an inexpensive mass product, otherwise the optical shortcomings of MAO cannot be justified.

What remains then is the option that one eyelet acquires only one pixel of the overall image. In other words, any intensity in the FOV of one eyelet is collected and gives rise to one point only. The consequence is that the location of the image point is determined by the eye architecture and is not an image of a real object point. Therefore, imaging optics are no longer necessary. All the optics has to do is to collect all light within the FOV of the eyelet. It is not necessary that this light be collected into a point (or rather an Airy disk), it could be a ring or an odd shaped figure.

For reasons of ease of manufacturing, it is here proposed to use light horns as optical elements. A light horn is funnel shaped and has reflecting walls. It does not form an image of an object point, but it concentrates light within its FOV. Rays impinging on the entrance aperture but coming from outside the FOV of the light horn are reflected back out through the entrance aperture.

d. Detector Array

Whatever the optical system may be--SLO (single lens optics) or MAO--it is certain that a large number of detectors are required. The human eye contains 10^8 detectors (rod and cones), insects have up to

20,000 eyelets with 7-8 detectors each which is considerably less, but still on the order of 10^5. Obviously for our MAO instrument we are looking for similar numbers.

A good question is, what exactly this number should be? A large number of detectors also requires a large processing capability. If MAO is to be a small system and an inexpensive mass product, it is not reasonable to connect it to a large computer. As a matter of fact, the computing should be done in the MAO device itself.

The trend of reduced number of detectors starting from the human eye at 10^8 down to 10^5 for insect eyes is probably caused by reduced processing capacity, the volume of the human brain is certainly larger than the insect brain by a factor which is considerably larger than 10^3. The consequence is that for our MOA instrument this number should be even smaller. Several times 10^4 is a reasonable assumption. (At present we are using $128 \times 256 \approx 3.3 \times 10^4$.)

The size of each detector for an imaging system should be equal to the size of the Airy disk created by the lens used. If the individual detector element is made larger, the resolving power of the system is determined by the detector's size rather than by the diameter of the lens.

The physical size of the Airy disk is:

$$A_d = 2.44\lambda(f\#) \tag{1}$$

A_d: diameter of Airy disk, λ: wavelength, while the angular resolution is

$$\alpha = 2.44 \frac{\lambda}{D}$$

(λ: wavelength, D lens diameter).

This means that for the human eye--depending on the wavelength under consideration--$A_d \approx 1.5\mu m$, which happens to be the size of some

of the rods and cones. Therefore, even a relatively small lens (D between 2 and 8 mm) forces the designer to use an enormous number of detectors (10^8 in case of one human eye) if the system is designed to be diffraction limited rather than limited by detector geometry.

There is no hope that such a large number of detectors could be handled in real time by any computer. Therefore, we have to resign ourselves to fewer detectors and consequently forget a diffraction limited system. Therefore number and size of the detectors will determine the resolving power.

Ideally one would like to have a curved detector array. For single lens optics it should be a concave array, as is the human retina, while for multiaperture optics it is a convex array. Unfortunately such arrays do not exist and the development of such an array would be very expensive. Therefore a flat array needs to be used. Based on above discussions an array having 128 x 256 (32768) detectors seems to be a reasonable device.

Figure 7 shows a schematic design of the MAO device using a flat mask and a flat array. However, this is for illustration only, the real MAO device has to have a convex mask surface. In Figure 7 the individual components of the MAO device are shown. They are, the field lens and the light horn as the optical system, the detector array, which has its own memory and a hard wired board which can manipulate the contents of the memory including an algorithm for recognition.

A detector array which has a built-in memory is already in existence—it is the optic RAM. We use at present the "IS32A Optic RAM" manufactured by Micron Technology, Inc.

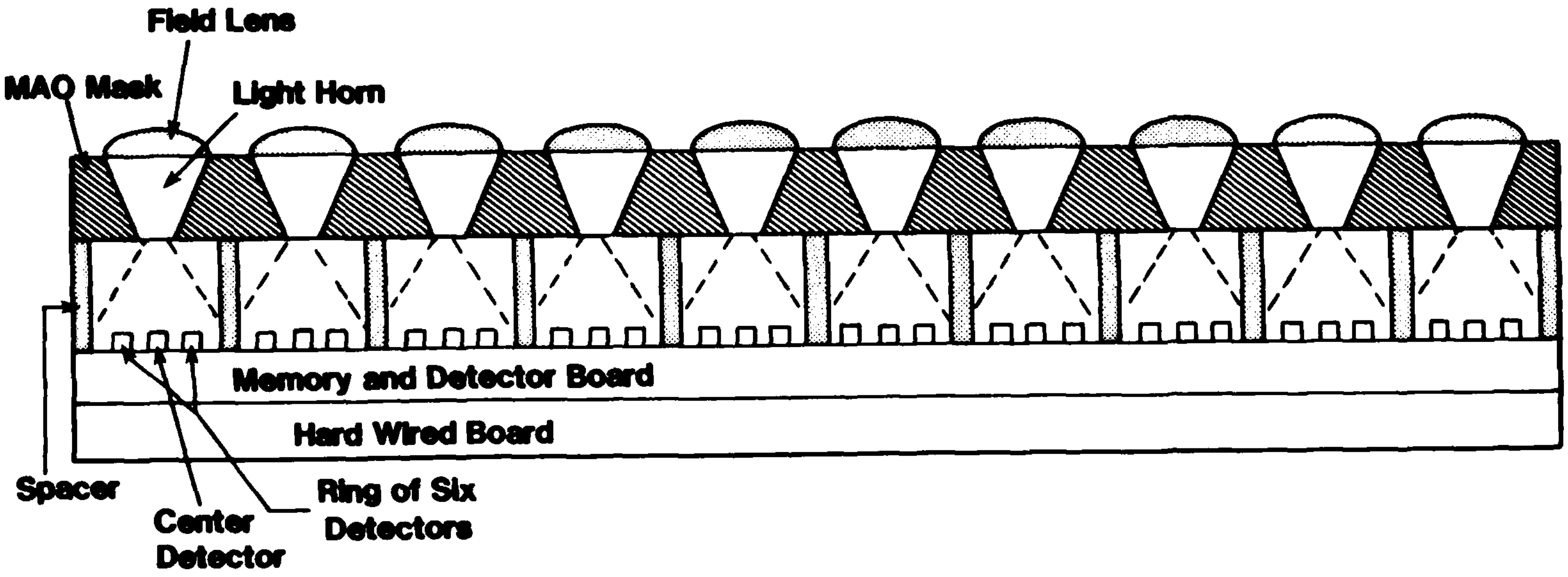


Figure 7. Multiaperture Optics (MAO) Device

Since a flat detector array is almost unavoidable and a convex surface is required, an adaptor is a necessity. This allows the building of the MAO mask (containing field lenses and light horns) in a convex arrangement. The adapter then couples the MAO mask optically to the flat detector array. The adaptor can be a regular faceplate using optical fibers, or if no suitable fibers are available for the wavelength under consideration, cylinders with reflecting walls may be used.

4. OPTICAL PREPROCESSING

a. Introductory Remarks

MAO devices consist of a multitude of individual eyelets. It is only reasonable to expect that each eyelet is more autonomous than an individual receptor of a single lens eye. "More autonomous" means that each eyelet can fulfill several functions and may or may not forward its findings to the main computing structure.

It is fairly obvious that the main problem in pattern recognition or even just image evaluation is the mass of data which has to be processed. Therefore any preprocessing is certainly worthwhile. Data processing is usually done by electronic means. It is proposed here that some preliminary data processing can be done optically. Strictly speaking, optical preprocessing is already practiced if the detector is larger than the Airy disk. This is actually an integration over several pixels, which the lens generates. Similarly, practices like placing a veil in front of a photographic camera objective to create a softer portrait qualifies as optical preprocessing.

However in MAO devices, due to the increased degree of autonomy of the individual detecting unit, more than simple integration can be done in terms of optical preprocessing. These various possibilities shall be discussed in this chapter.

b. Overlap

For the simple apposition eye, as considered for our MAO design, the FOV of an individual eyelet should give raise to one pixel only. In other words, any intensity--whatever it may be, a point light source or an extended light source--found in the FOV will produce one pixel of the image to be collected. However, as will be shown in a

later chapter, in the case of the light horn it makes a difference where within the FOV a point light source is located and in the case of a parallel beam, under which angle it is incident. Therefore the possibility exists to extract some more information out of the observed intensity even though the light horn is non-imaging. This, of course, requires a multitude of detectors rather than the one which would be required to observe just one object point.

If such a design decision, namely to use more than one detector per eyelet, is made, another possibility opens up which is to allow overlap of the FOV's of neighboring eyelets. If this option is exercised, some sorting of the received information using the several available detectors becomes necessary. In this case light coming from a given point in space is received by more than one eyelet and therefore it is conceivable that coincidence methods may be used during the detection process. Such a scheme could certainly be termed as advanced optical preprocessing. For this reason FOV overlap shall be discussed now in somewhat greater detail.

Figure 8 shows a central detector (c) surrounded by 6 peripheral detectors (1-6). The circle (IFOV) represents the field of view which is perceived by the central detector only. The light horn shall be designed in a way that the field of view of the central detector is <u>not</u> overlapping with the one of the neighboring eyelet. This part of the FOV shall be called individual FOV (IFOV). However, the other detectors will perceive the rest of the FOV of the eyelet. The FOV which all seven detectors will perceive shall be called total FOV (TFOV). The TFOV partially overlaps with the TFOV's of the neighboring eyelets. The circles shown in Figure 8 are arbitrarily selected

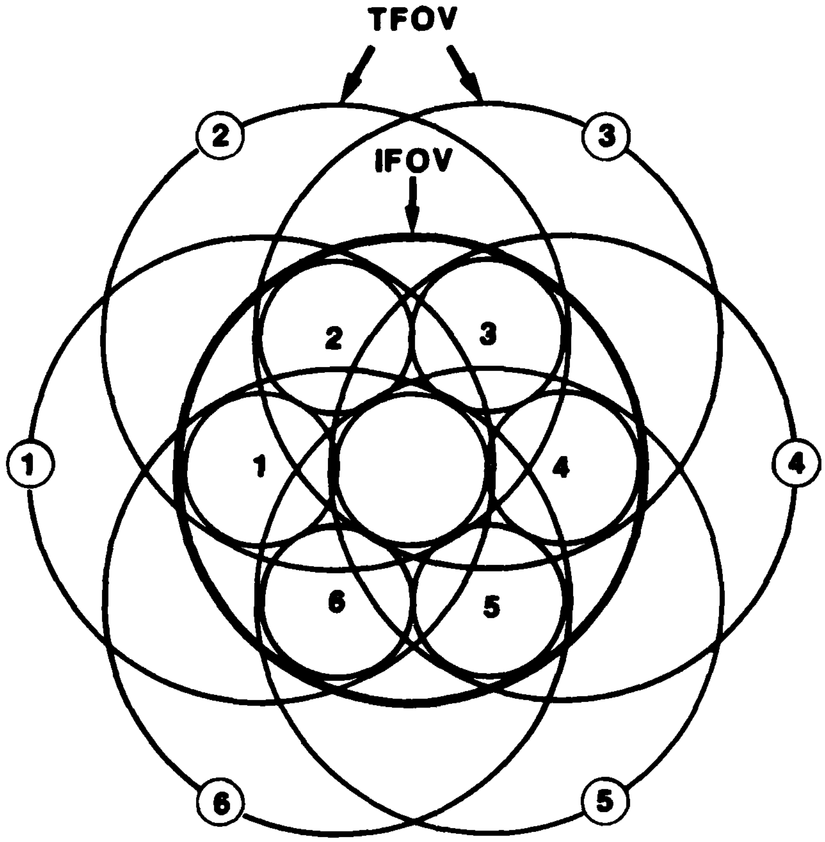
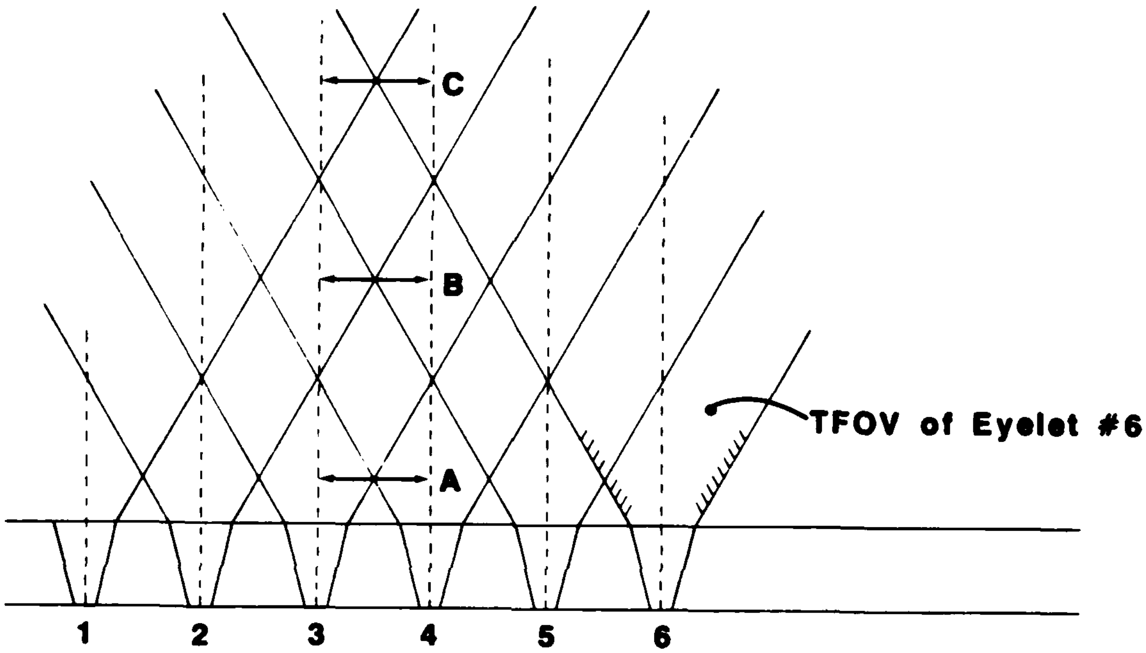


Figure 8. FOV Overlap

for a certain object distance. The diameter of these circles increases with the object distance as shown in Fig. 9. As can be seen for a flat mask the greater the distance, the more eyelets overlap. (The same situation would hold for a mask having only minor curvature.) The consequence is that an object becomes actually larger if its distance from the eye is increased, unless steps are taken to use only the IFOV's for pixel formation, meaning only the central detectors should be used for pixel definition. The rest of the detectors are to be used for other tasks. One such task could be to probe the intensity distribution of the "footprint" of the light horn.

A point light source within the FOV of eyelet (TFOV) would illuminate all 7 detectors albeit not uniformly. The intensity distribution would depend on the location of the point light source. Only a large extended light source at infinity would cause a timely uniform illumination of all seven detectors. Therefore, for most applications one expects an intensity distribution pattern. Once a certain distribution pattern for a certain situation is known for a given light horn, some conclusions can be drawn from the output of the seven detectors. There is, of course, only a very limited number of conclusions which have to be compared to the large number of intensity combinations which could be expected if the seven detectors were illuminated by a large single lens and therefore would constitute 7 pixels of an image. Since, in the case of the light horn, the information obtained by the illumination of the seven is of a different, more general nature than the information consisting of seven pixels obtained by a single large lens, one can say that the light horn indeed performed some optical preprocessing.



Distance A: FOV of #3 and 4 (2 pixels)

Distance B: FOV of #2,3,4 and 5 (4 pixels)

Distance C: FOV of #1,2,3,4,5 and 6 (6 pixels)

Fig. 9: Increase of Pixel Number with Distance

c. Distance Perception

As pointed out above, allowing FOV overlap creates the possibility of collecting information which is in addition to the mere fact that one certain pixel exists and has a certain intensity. This additional information can produce knowledge concerning distance of an object, or motion of an object or can be used to reduce noise by using coincidence techniques.

Figure 9 shows that the overlap increases with distance. The figure also shows that for a given object size there exists a maximum number of detectors which "see" the object when placed at a large distance.

For a curved mask, the true size of an object can be obtained from the detectors, which have a non-overlapping FOV (refer to Figure 8). For those detectors the image will become smaller with distance, meaning the farther away the object, the fewer the number of pixels it will contain. On the other hand, the number of pixels seen by detectors having overlapping FOV will increase. Therefore the ratio of this number gives a relationship for distance of the object.

d. Motion Detection

Motion detection is widely employed using single lens optics. The most straight-forward approach is to subtract two consecutive frames from each other, threshold it for noise and if a residual intensity is obtained the conclusion is that something has moved or something has changed intensity. For applications to non-selfluminescent objects, the conclusion that motion has taken place is probably correct, since a change in illuminating intensity would affect all objects similarly.

Obviously an SLO method will be insufficient if applied to luminescent objects. In this case one would have to recognize the object first (at least its outlines) and then recognize it again in the next frame, then compare their locations before one can be sure that the object has actually moved. This requires a substantial effort in image evaluation. However it is easy to see that a measurement of intensity ratios between two different spatial locations will not suffice, since the reason for a change in intensity may be either a movement or fluctuation in luminescence.

However, in the case of MAO, the overlap of FOVs opens up an avenue to use intensity ratios only, rather than having to recognize the object first and then trace its movement. The reason is that if the object changes its intensity, all the detectors in the overlapping part of the TFOVs will see a proportional change. If the object moves, some of the TFOVs will no longer see it, some will see less and some will see more. Therefore, an intensity ratio measurement will indeed suffice to detect motion.

e. Coincidence Detection

The FOV overlap can also be used to analyze short time phenomena. If there should be a light flash in a given point in space, a single large lens would deliver this light flash to one detector only. (Asuming the object point produces an Airy disk which is the size of the detector). In case of MAO several eyelets will see the light flash since the TFOVs overlap. It is predictable how many and which eyelets should see the flash. Therefore, from ratio of the number of eyelets which actually report seeing the flash and the number of eyelets which actually should see it, the probability that the observed flash is a signal rather than noise can be computed.

Requiring multiple observations at a given time is known as coincidence detection. Since probabilities multiply, this is a very powerful technique. E.g., if the signal to noise ratio (SNR) is known to be 1 for a given phenomena, then if only one detector is exposed to it the probability that the observed output is caused by noise is 0.5 (50%). However, if two detectors are exposed and report an output, the probability that it is caused by noise is only 0.25 and in case of 3 detectors it would be 0.125, etc.

5. APPLICATIONS FOR MAO

a. Introductory Remarks

Since MAO exists in nature, it is probably safe to say that after many million years of evolution the optimum configurations for such a design have been achieved. Therefore a man made MAO device will have to resemble an insect eye to some degree. Obviously one wants to utilize the wide FOV, which eliminates the need for scanning and due to the requirement for a reasonable resolving power the total FOV has to be divided in a large number of individual FOVs which leads to small entrance apertures. (Large entrance apertures could be used, of course, but then the need for a multitude of them becomes questionable.)

Considering all this one can expect the MAO eye to be the size of a postage stamp with individual entrance apertures of 100 μm for visible light. The smallness of the eye would make it prohibitively expensive unless microchip technology is used.

To point out the potential of MAO, we will discuss briefly some possible applications of MAO.

b. General Camera

A multiaperture camera could be used as an all purpose eye for a vehicle (cruise missile, ships lookout, robot, land mine detector, tailguard, etc.). Since a hard-wired board, which can contain recognition codes, will be an integral part of the eye, it can recognize objects and give steering commands to a vehicle.

c. Motion Detector

A MAO eye in the shape of a hemisphere can be mounted on the ceiling of a room to be safeguarded. The eye will be programmed to

check for motion rather than recognition of shapes. This is probably the most simple application for MAO. As can be gathered from the discussions earlier in this report the motion detector is very powerful since it can work with coincidences. The algorithms for it are much simpler than the ones for recognition schemes. (This would be a very simple device which could be mounted on ships to look out for moving objects.)

d. Tracking and Measuring

Unpredictable phenomena like meteor traces or lightning paths can be followed by a hemispherical eye, similar to the motion detector mentioned above. Only this time the eye is programmed for recognition of simple shapes. Such an instrument could be used to do statistics on lightning or meteor showers. It could also be used for solar research although the sun travels slower. In this case the size of an individual FOV will be chosen so that it will just be filled by the image of the sun. The rest of the eyelet will then be used to collect data concerning the scattered radiation, cloud coverage, etc.

e. Robotics

One problem encountered with robotics, which is new compared to conventional automation, is that the robot can move its arms freely and it can smash into objects or people. Therefore a visual system to prevent such mishaps would be very desirable. It is easily seen that a TV camera mounted on a central location (head) of the robot would require a large amount of computing power to recognize objects and correlate them in respect to the position of the arms. Obviously it is impractical to mount a TV camera on the moving arm. However a postage stamp sized MAO eye can be easily mounted on the "hand." It

will not be bothered by acceleration and deceleration. With a pair of these MAO eyes mounted triangulation can be performed which would tell the system how far away the interfering object is. Obviously only the fact that an interfering object is present needs to be detected, not what it is. Therefore a simple recognition scheme which is of course handled in the eye itself, will suffice. Also since MAO is non-image forming, focussing of the eye is not required, which is very important for this particular application.

A hand mounted eye could also be used to find and identify a certain part which the robot needs to install. Here of course a more sophisticated recognition scheme will be necessary. However, since a-priori knowledge exists, how the part looks like, the peculiarities of MAO can be used, so that the eye would only recognize the desired part while all other objects will be classified as interfering objects and will only become a concern if they are close enough to interfere with the movement of the arm.

f. Parts Inspection

As can be sensed by reviewing the applications discussed, so far MAO is best applied to situations where low resolving power and simple recognition schemes are inadequate. A very good example is parts inspection. For example, if one wanted to inspect beverage bottles on the production line for cleanliness, absence of cracks, and absence of foreign mass, the recognition scheme seems to be so complicated (and therefore expensive to develop) that still, in many instances, a human inspector is used. MAO however fills these requirements with ease. Each individual FOV inspects a certain volume element in the bottle. It is easy to define which ones have to be empty and which ones do

not. If there is a foreign object in the bottle, only this fact has to be detected, rather than the shape of the object itself. Therefore, if one or more of the FOVs show a low intensity which should show high intensity (empty) this is already sufficient to reject the part. A smudge on the surface of the bottle can be detected with intensity ratios between neighboring eyelets. The same is true for cracks. It is also easy to adjust for different glass coloration by simple averaging over the eyelets which view the empty part of the bottle.

g. Gazing Sensors

Future military requirements will contain a greater necessity to detect in which direction (e.g., in respect to his helmet or in respect to the airframe) a pilot looks. For this reason the movement of his eyes has to be monitored and the center of the pupil has to be recognized. A MAO device is small enough to be mounted in the rim of the helmet and observe the pilot eyes without interfering with his vision and without adding an undue amount of weight to the helmet. It is even possible to mount the device in the lower (unused) part of the eyelgasses. The recognition scheme is very simple and can be accomplished inside the MAO device.

h. Blind Man's Eyes

A set of eyes which recognizes objects and points out kind and position of such objects by verbal communications would be an invaluable aid for blind people. In principle this could be accomplished by two TV cameras served by a large computer. Obviously such a system would not be very practical. However MAO devices are small enough that they could be carried by a person. Recognition is done in the MAO eye already. What still needs to be added is a speech synthesizer which translates the output of the MAO device into words.

Only simple shapes would have to be recognized. For example, if an object is dead ahead the shape of the object is not very important but its distance is. This distance can be obtained by triangulation. Also moving objects are of importance. Any movement has to be considered as a threat and therefore detection of movement (motion detector) could be done without recognition of the moving object. Here recognition of simple shapes goes along with low resolution and makes this a practical device for a blind person to wear. Only a few words would be required for the speech synthesizer. They could be pre-stored in a chip and called when needed.

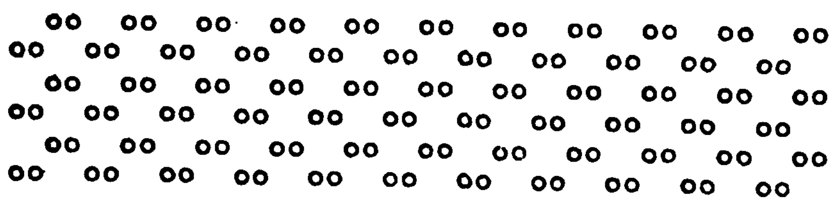
i. Application to X-rays

Regular X-ray "images" are actually not images but shadowgraphs. CAT-scans are computed images. If a collimator mask is added to the MAO device it becomes an X-ray imaging device. The collimator mask is made of lead and has a multitude of small cylindrical holes in the lead. The diameter of these cylinders is equal the entrance pupil of the individual MAO eyelets and the axis of each cylinder coincides with the optical axis of the particular eyelet it serves. The light horns in the eyelets are filled with a scintillation material. The light generated by the X-rays is detected by the detectors mounted underneath the light horns. Such a MAO device could be built in larger sizes so that the total aperture would be larger than a pinhole in an X-ray pinhole camera.

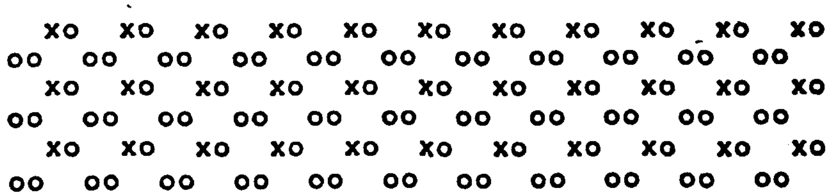
6. EXPERIMENTAL DEVICE

The multiaperture device consists of a detector chip and the MAO mask. The detector chip is an optical RAM manufactured by Micron Technology, Inc. The designation is IS32A OPTICRAM. It nominally contains two arrays of 128 x 256 (each) silicon detectors although not all detectors are actually in place. Sensitivity is 2 μJ/sq. cm. at 900 nm. Each detector is 6.4 x 6.4 micrometers in size. They are arranged as indicated in Figure 10a. The distance between rows is 6.8 micrometers (center to center). The distance between two neighbors in a given row is 8.6 micrometers center to center. The somewhat unconventional arrangement of detector forces the user either to fill in the missing pixels (in Fig. 10a) by best guesses or omit certain detectors as indicated in Fig. 10b. Now only the detectors marked by an X are used. This reduces the array to 64 x 128 detectors. Each detector element can be individually addressed. Figure 11 shows a photograph of the IS32A chip and a chip with the MAO mask mounted.

The MAO mask consists of a glass plate, which features a large number of cylindrical holes. The diameter of each hole is 100 micrometers. The distance between the holes is about 75 micrometers (150 micrometers from center to center). Figure 12 shows a microscope photograph of the mask, while Figure 13 shows a sketch depicting how the mask is attached to the chip. The mask is bent with a radius of 75 mm so that the angle between neighboring eyelets is 0.12 degrees. The mask has a diameter of 13 mm although only an area of about 2 x 5 mm (the size of the detector array) is used.



10(a)



10(b)

Fig. 10. Arrangement of Detectors on Optic RAM

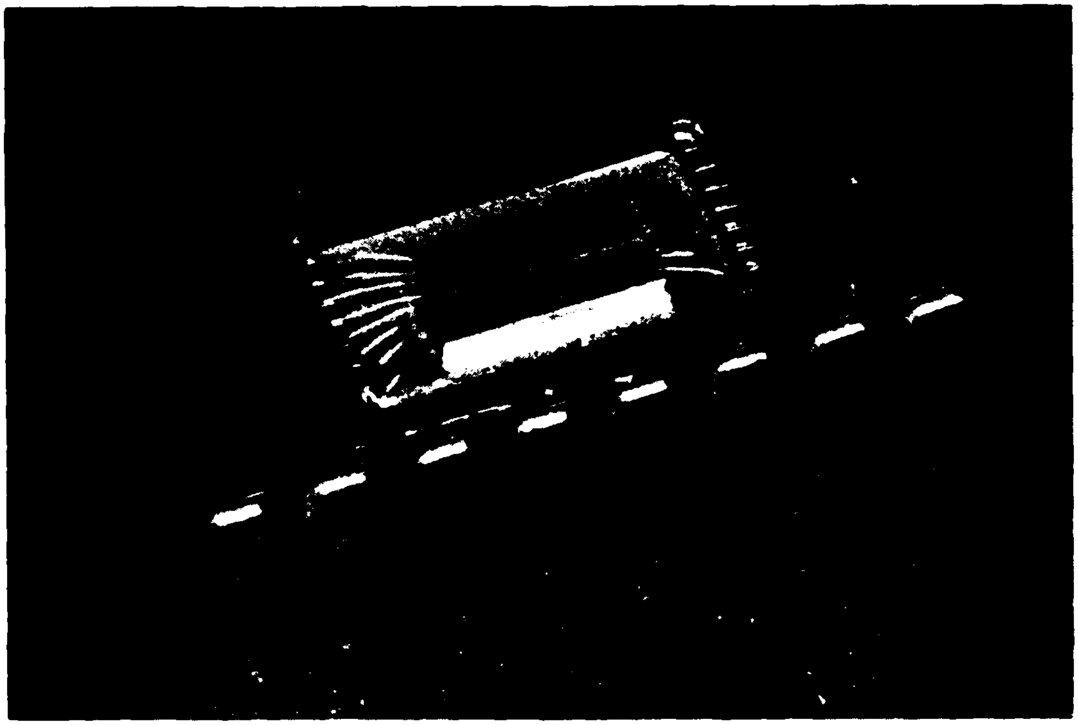


Figure 11. IS32A-Chip With MAO Mask

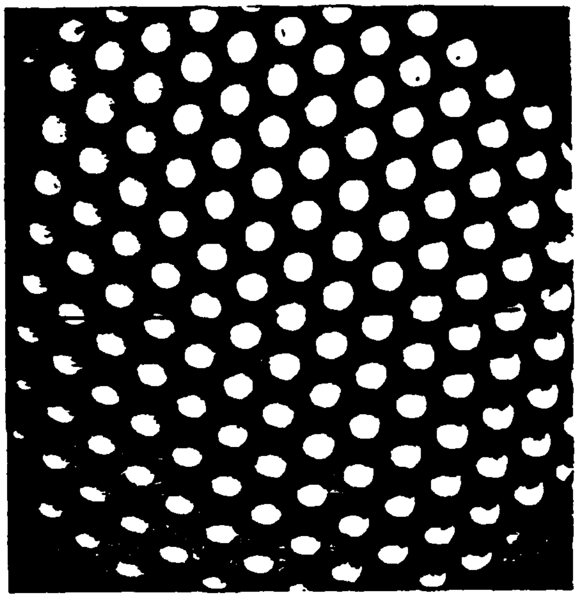


Figure 12.
Microscope Photograph of MAO Mask

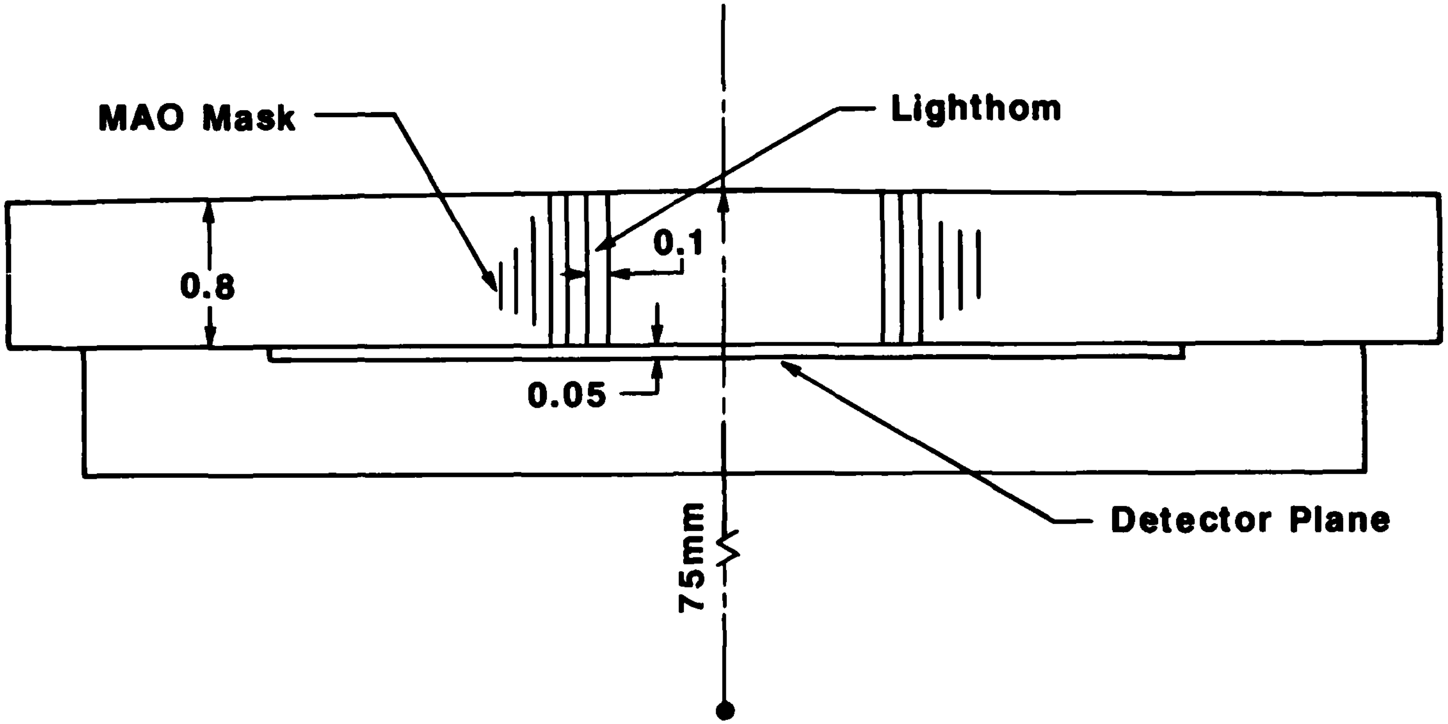


Figure 13.

MAO Device, Dimensions in mm.

Since the center distance between holes is 200 micrometers, a matrix of 10 x 25 holes is located over the detector array. Each hole should have a footprint containing 11 x 11 spaces for detectors which, however, are not all occupied. Figure 14 shows such a 11 x 11 field. The "footprint" of the round hole is drawn slightly larger in order to account for the small gap between exit aperture and detector plane. The detectors which are actually in place are marked with "x." The detectors actually used are indicated by a circle around the x. Counting the actual detectors, one finds that there are 2 in the 512 direction and 6 in the 128 direction. As will be seen in the next chapter, the bit map reveals that on the average 2.25 x 7 detectors are effected by one hole giving an aspect ratio of approximately 3:1. This is the actual "footprint" of the hole, meaning those detectors directly underneath it which are used. There are, of course, other detectors which are underneath void spaces (the spaces between holes). Since there is a small gap (0.05 mm) between the hole exit and the detector plane, oblique rays, namely those which have been reflected one or more times at the walls of the individual holes will illuminate the detectors located under the void spaces. The walls of the holes are dark glass, so the reflected rays will be of diminished intensity. The computer program will let the charges on the detectors accumulate (soak) for a selectable exposure time and then read the values above a certain threshold value. Therefore, if the exposure time is kept short only the detectors directly underneath the holes will report intensity, while at longer exposure times the detectors underneath void spaces will also see some light. In other words, at short exposure times a target will appear to be depicted by individual dots

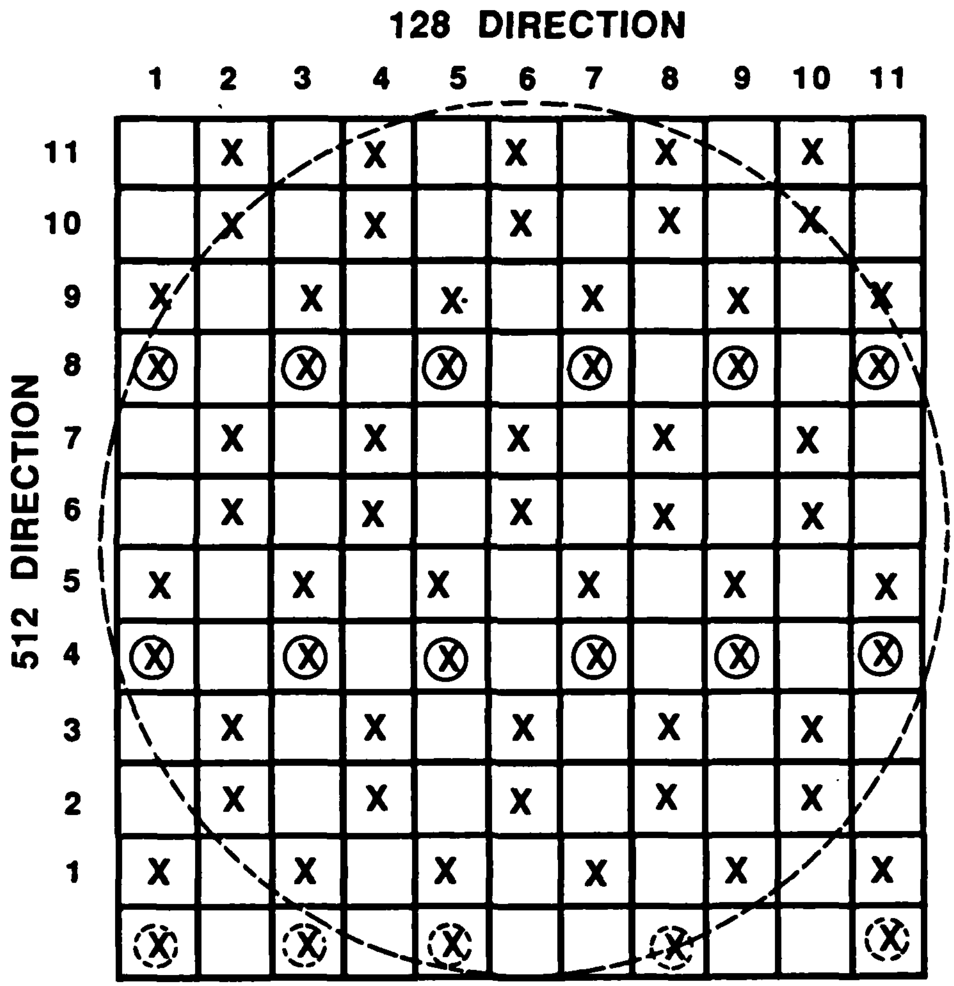


Figure 14. Detectors Used

(footprints) while at longer exposure times these dots will grow together to a homogeneously filled area.

It would be preferable, of course, to have conical holes (light horns) instead of cylinders. Also, the walls of the cones should be coated with a highly reflecting layer. In addition, the cones should be closer together than one diameter of the entrance aperture. We will be able to accomplish this in the near future. This should improve the performance of the device drastically.

The way the mask with the cylindrical holes were made limited the radius of curvature and therefore the FOV. We anticipate having masks with shorter radius of curvature also available in the near future.

7. PERFORMANCE OF THE MAO DEVICE

In the following a few examples of the performance of the present MAO device are given. During the present effort no attempt was made to compensate for the FOV overlap. Therefore the device works best at close distances. All of the images shown here are of close distance. First we will explore how many detectors are within the output cone of one light horn. These output cones overlap since there is a small gap between detector and MAO mask. Therefore, in regular operation the detectors located inside an image are all illuminated and a uniform exposed area is returned on the monitor screen. However, it is possible to make the footprints of the individual light horns visible by underexposing and thresholding. In this way only these detectors which are directly under the opening of the light horns are visible. This can be seen in Figure 15 which is an underexposed "plus" sign. The individual spots represent the footprints of each lighthorn involved in making the image. In order to make the individual detector in each footprint visible, the image is presented as binary image in Figure 16. The pixels indicated by a "1" are the detectors which are illuminated. As can be seen, each footprint contains two rows, sometimes three rows of "1," while there can be as many as 8 columns of "1." It is, of course, known that the output aperture of each light horn is circular. The distortion experienced is a consequence of the way the detectors are oriented on the chip. Of course, once this is known, allowance could be made in the software to correct this distortion. However, since the MAO device is not intended as a camera which produces an image for a human observer, but as a device which

Figure 15. Underexposed Plus Sign.

BIT MAP LISTING FOR FILE bifcro75.dat

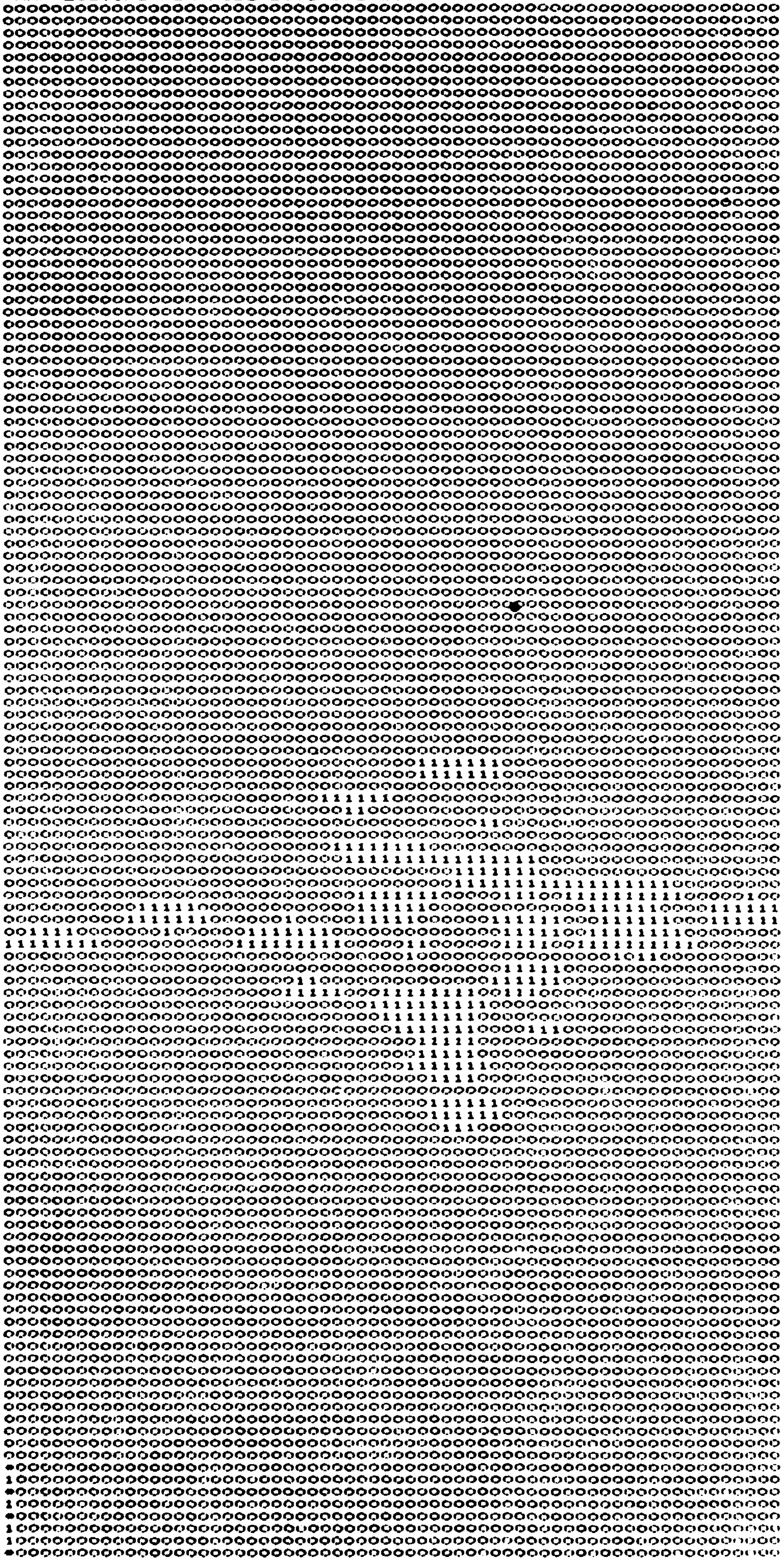


Figure 16. Binary Image of Fig. 15.

recognizes an object and reports the recognition, any distortion, as long as it is consistent, is of no consequence. However, during the research program we need to monitor what the device sees and for this reason, we are displaying these images on the monitor. Therefore, when viewing these images, one should realize that this distortion exists and should make allowance for it.

Figure 17 again shows a "plus" sign (white on black background), this time correctly exposed. The two bars, horizontal and vertical, should be the same width, but as can be seen the horizontal bar is about 3 times wider than the vertical bar. If one considers that the typical footprint shown in the binary image consists of 2.25 rows and 7 columns, about a 1 to 3 ratio, one can explain the distortion.

The same effect can be seen when a rectangle having sharp edges (Fig. 18) is displayed (this time black on white background). The vertical edges are much better defined than the horizontal edge. The vertical boundry is sensed by 8 detectors, up and down is determined by an average of 2.25 detectors.

Along the same lines; the image of a sharp point is shown in Figure 19 (black on white background). The point is clipped for the same reason, also the edges show a structure which is a consequence of the unequal number of detectors. Finally in Figure 20 an extremely close view of the grid lines on a slide containing a graph is given. Again the horizontal lines appear wider and less defined than the vertical lines. A printout of the binary image shows (Figure 21) about the same appearance. However, having the binary image available, there is no doubt where the real lines and their intersections

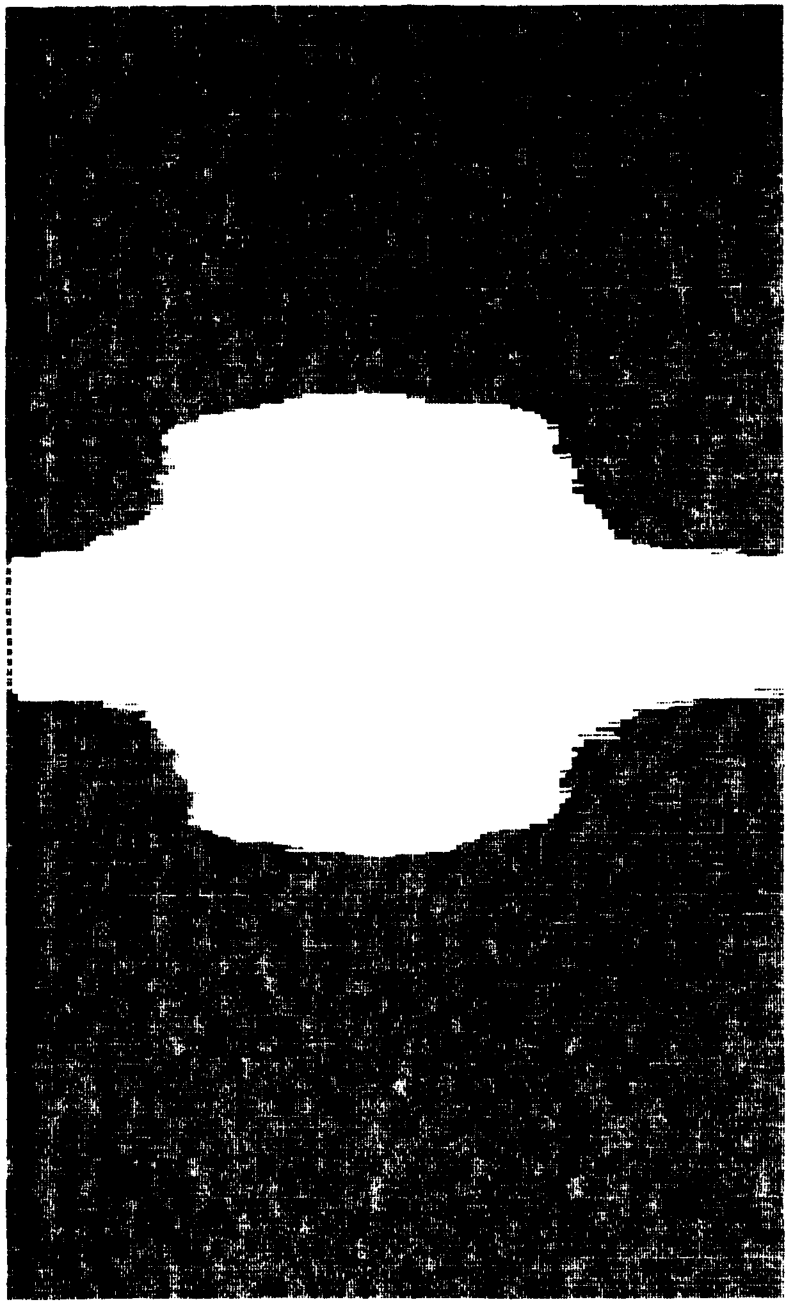


Figure 17. Correctly Exposed Plus Sign.

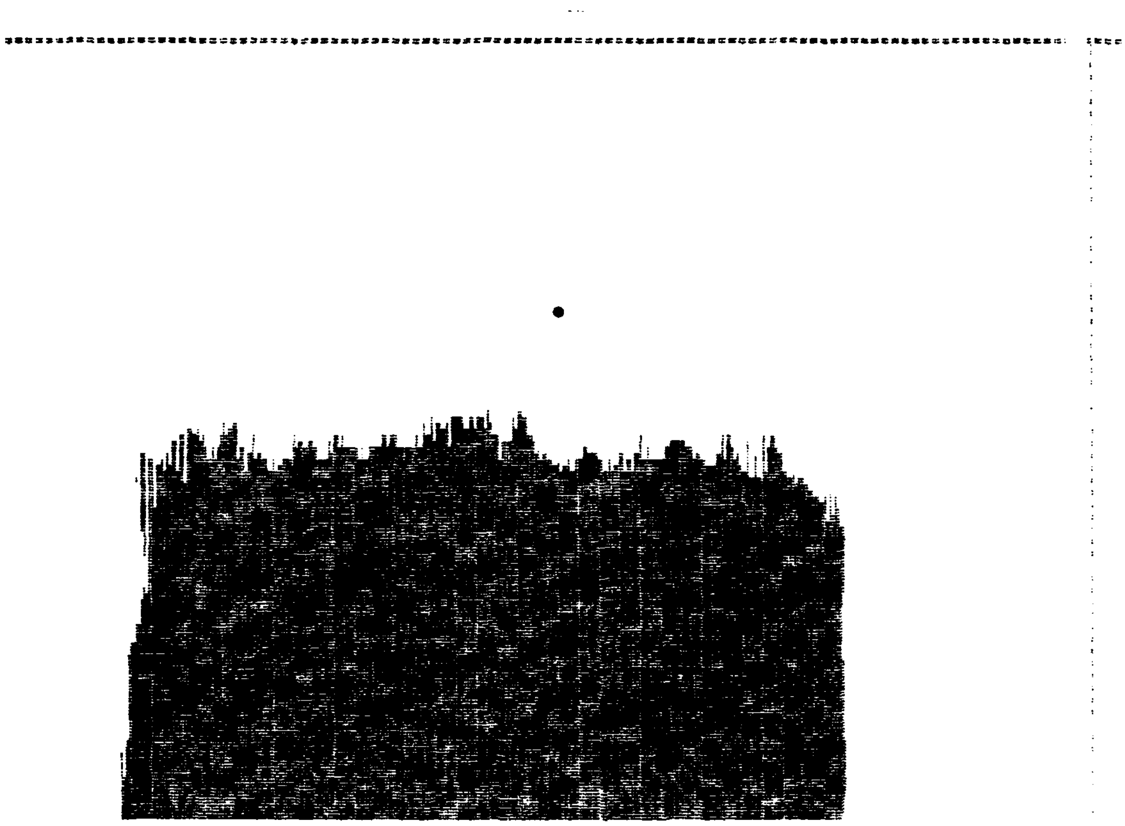


Figure 18. Rectangle Having Sharp Vertical Edges and Less Sharp Horizontal Edges.

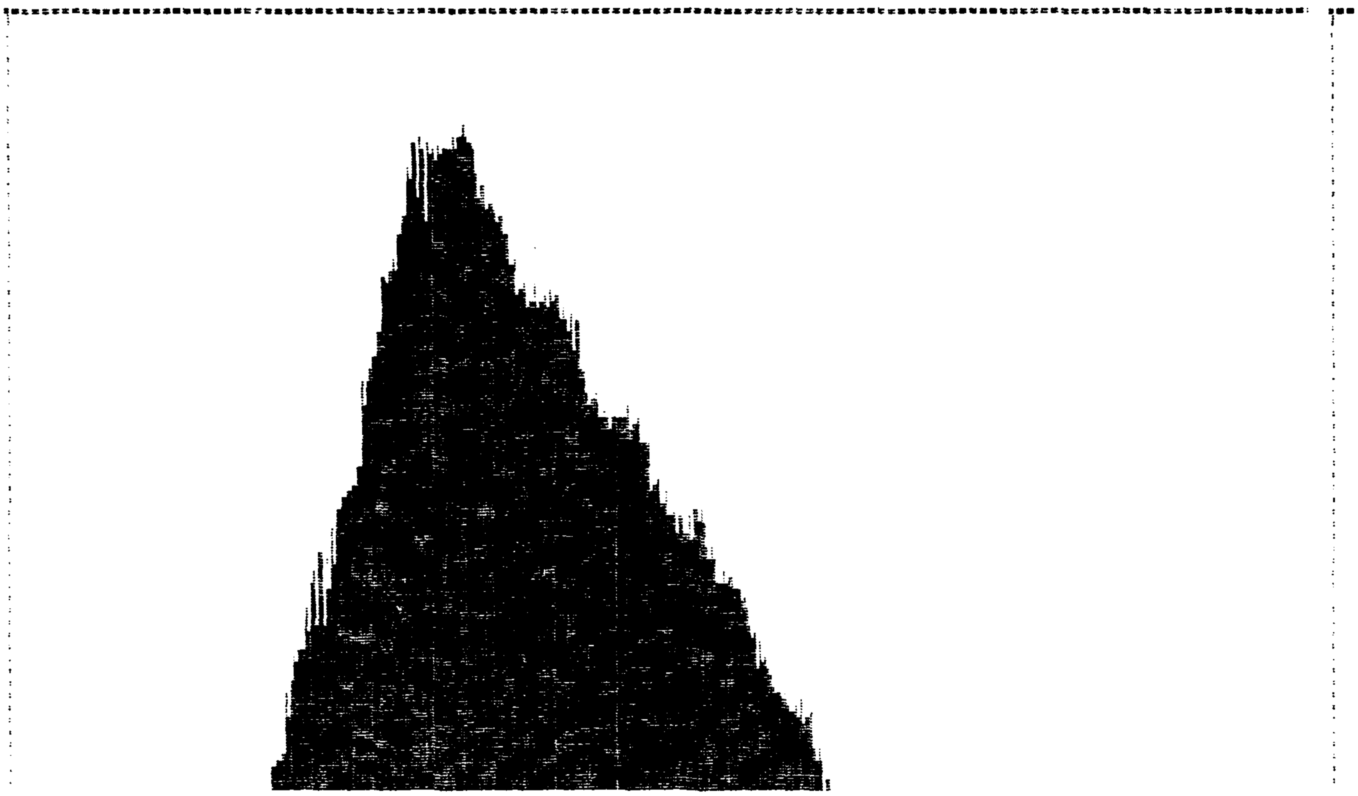


Figure 19. Sharp Point.

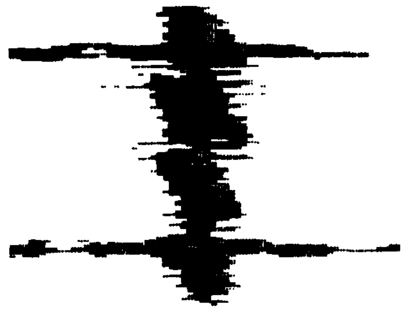


Figure 20. Grid Lines.

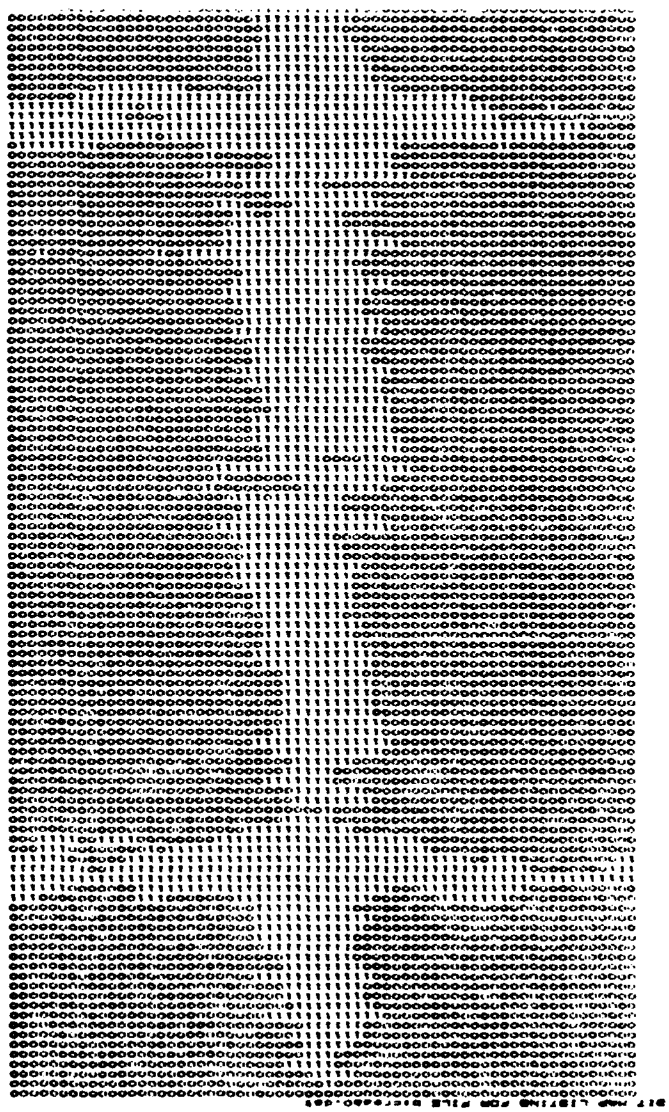


Figure 21. Binary Image of Fig. 20.

are. A simple algorithm could be written to remove the excess "1" and leave only one line of "1" standing, giving a perfect image, although the acquired image was distorted. This requires a-priori knowledge that the grid system is indeed continuous so that it can be assumed that the occasional "0" interrupting the lines is caused by noise or damaged detectors, rather than by an imperfect original. However, such assumptions are even made by the human recognition system. It's tendency to fill out apparent gaps in lines is well known.

8. PATTERN RECOGNITION PROCEDURE

A. Concept

As pointed out before, the MAO device is not intended to be a camera producing an image that would be viewed by a human observer. Rather, it is a digital device capable of recognizing a pattern, whereby the necessary circuitry and ROM should be on the same chip which houses the MAO mask. In the following we are simulating this circuitry on a PC, which is the reason why we can also display the images that the device "sees."

The concept of the pattern recognition scheme used at present is based on the fact that a MAO device will necessarily present a small number of pixels. The optical design of the mask has to be aimed at producing pixels on optimum locations and the pattern recognition scheme has to try to make the best out of the information presented.

This is accomplished by not expecting to find and not accepting if offered unnecessary details. Therefore, the concepts of the recognition scheme consist of assumming that any pattern encountered consists only of a sequence of rectangles. The picture language used has only one word "rectangle." The information describing the object therefore consists of

1. Number of rectangles contained in the pattern.
2. Aspect ratio on each rectangle.
3. Orientation of the rectangle (meaning the longer side points either in the x or y direction).

Therefore, an encountered pattern will be disected into an assembly of rectangles. The procedure for disection is held flexible and is at

present subject to operator input. After a pattern of several rectangles is established, their aspect ratios are computed. This results in a set of numbers which is the ID number of the pattern to be recognized. The memory contains a catalog of ID numbers of objects of interest. An attempt for a match can be made against these stored ID numbers.

B. The Algorithm

The information is available as a binary image. For the present it is assumed that each "footprint" represents one pixel of the image received. At a later date more information than this will be recovered from the content of one footprint. However, for the time being the only information used will be whether the pixel is present or not.

For the algorithm used it is assumed that each footprint can contain 3 x 3 detectors. At the images presented above actually only 2 x 3 detectors are used, however, examining Figure 14, one can see that a 3 x 3 matrix could indeed be established by readdressing the detector chip. Since the chip is a RAM, this is indeed possible.

For the first step in the recognition scheme a decision has to be made which pixel is considered to be present and which to be absent. Therefore, for a pixel to be present one requires that a footprint has to contain a minimum number of "1." The program leaves it up to the operator to decide how many "1" are required, although in a future version this number may be picked by a trial and error method. However, at present the operator can specify 1 through 9.

For easier visualization of the functioning of the program, a set of synthetic data is presented in the following figures. Figure 22

```
Would you like to re-examine this pattern?--'Y'
n

A>birec
DATFILE: fake1.dat
PASFILE: fake1.pas
To analyze a previously created [ ].PAS file, enter '1'
To analyze a new [ ].DAT file, enter '2'
2
reading in the data...

Would you like to see the data set?--'Y'
y
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
11111111111111111111111111111111111111111111111111111111111111111100
11111111111111111111111111111111111111111111111111111111111111111100
11111111111111111111111111111111111111111111111111111111111111111100
11111111111111111111111111111111111111111111111111111111111111111100
11111111111111111111111111111111111111111111111111111111111111111100
11111111111111111111111111111111111111111111111111111111111111111100
11111111111111111111111111111111111111111111111111111111111111111100
11111111111111111111111111111111111111111111111111111111111111111100
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000000000000000011111111111111111111111100000000000000000000000
00000000111111111111111111111111111111111111111111111111100000000000
00000000111111111111111111111111111111111111111111111111100000000000
00000000111111111111111111111111111111111111111111111111100000000000
00000000111111111111111111111111111111111111111111111111100000000000
00000000111111111111111111111111111111111111111111111111100000000000
00000000111111111111111111111111111111111111111111111111100000000000
00000000111111111111111111111111111111111111111111111111100000000000
00000000111111111111111111111111111111111111111111111111100000000000
00000000111111111111111111111111111111111111111111111111100000000000
00000000111111111111111111111111111111111111111111111111100000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000
```

Figure 22. Synthetic Data, Airplane-like Structure.

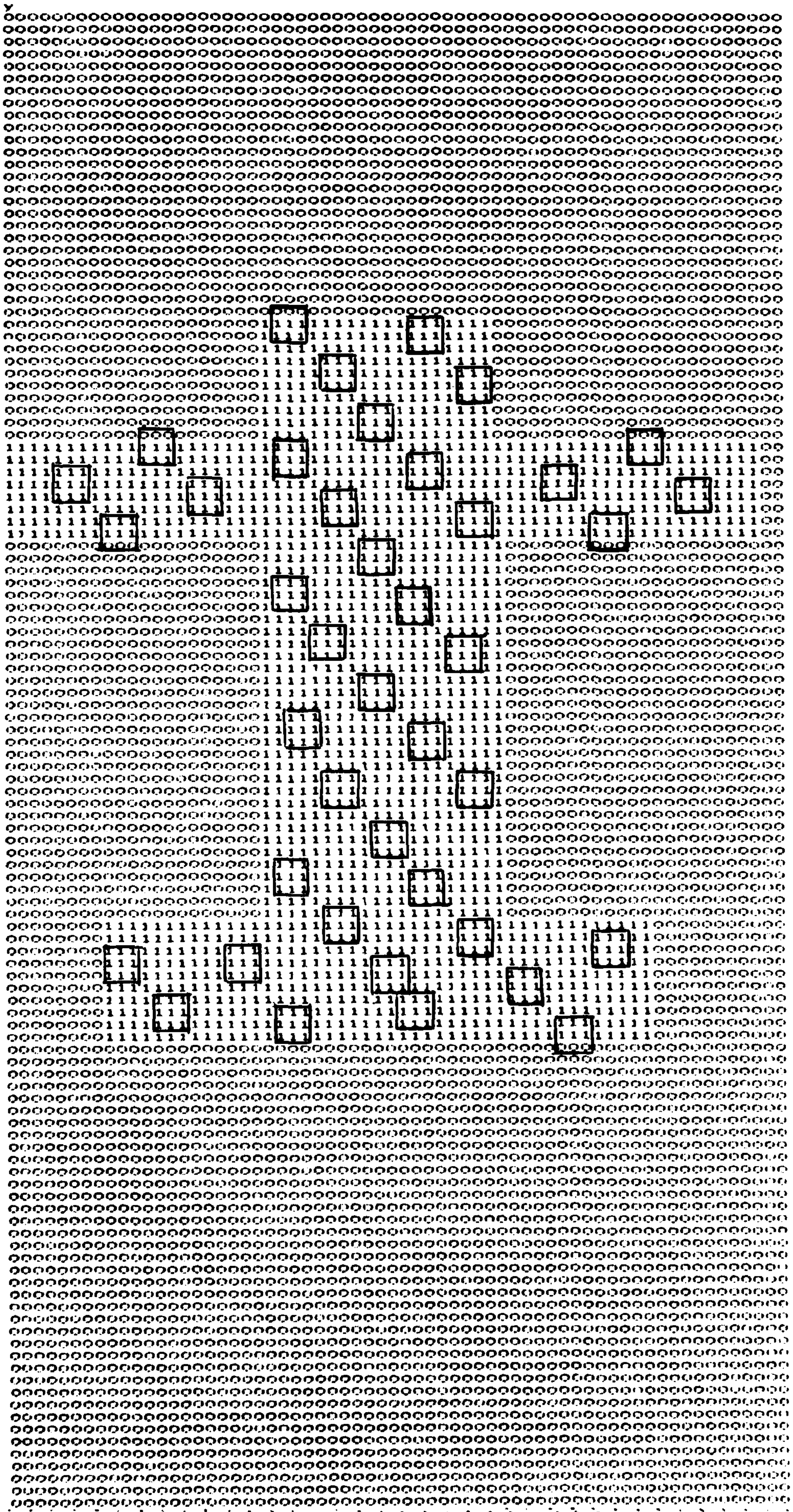


Figure 23. Overlay of Hole Patterns Over Fig. 22.

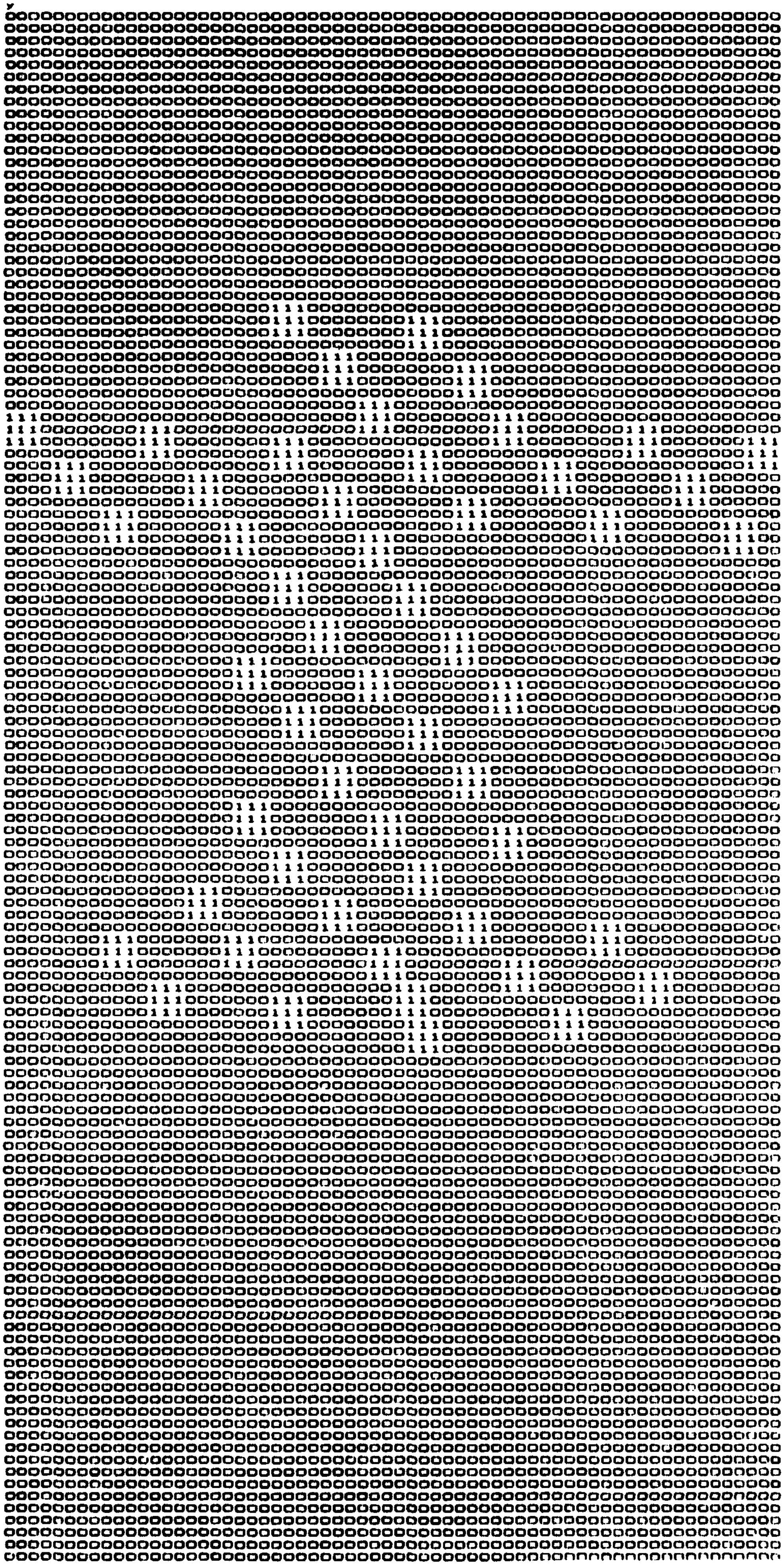


Figure 24. All Footprints Filled With 9 Binary Ones.

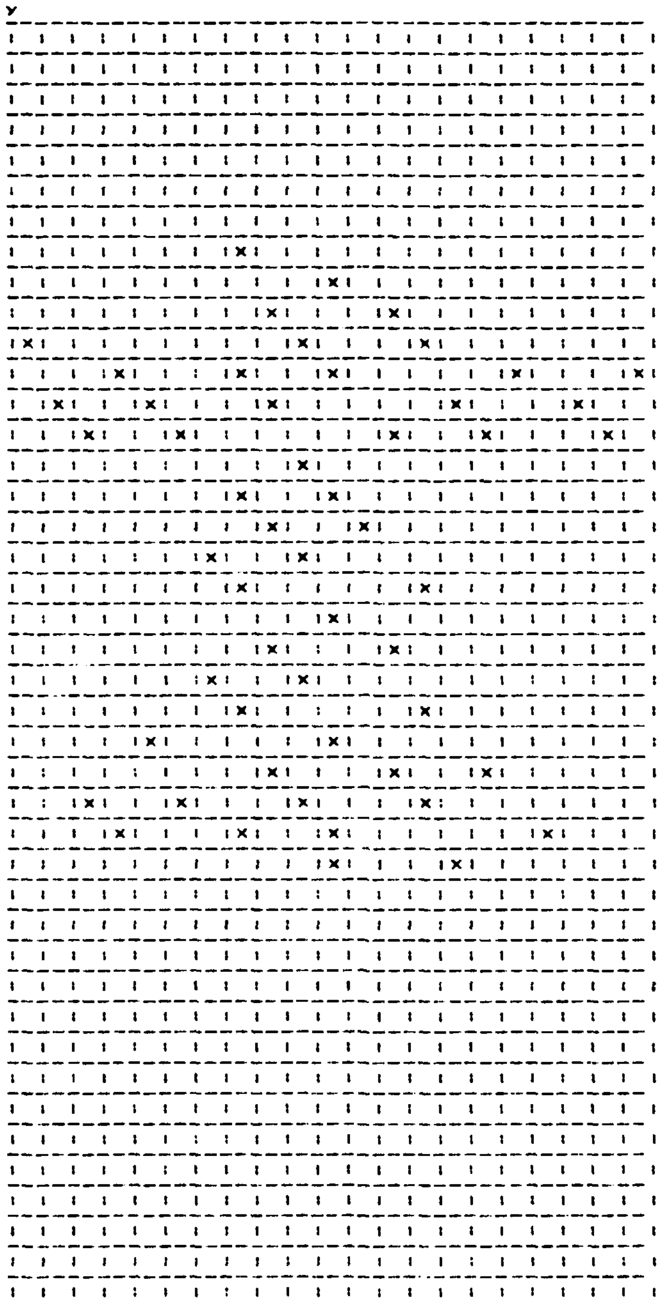


Figure 25. Coarse Map of Fig. 24.

shows an airplane-like structure in the form of a binary image. An overlay of the hole pattern is given in Figure 23.

As can be seen, there are some footprints which contain one binary "1", while there are others which contain six or three. The operator now requires that 6 binary ones are adequate for a pixel to be present. After this input is made, all the footprints which qualify are filled up with 9 binary ones. This is depicted in Figure 24. The next step is to divide all positions by 3, which generates the map in Figure 25.

The next step is to enter a procedure to disect the so reduced pattern into a set of rectangles. To demonstrate the procedure we pick an arbitrary pattern shown in Figure 26. We treat each line as a line of the rectangle to be formed. Therefore, we are only interested in the boundary of the lines, and not whether the line is filled or not. With this we find the first line to be 8 units long and the second 10 units, etc. The operator now chooses a number which we call "section delimiter". The procedure consists of determining if the line following the present line is larger than the "section limiter." If "no," this next line will be part of the present rectangle. If "yes," a new rectangle will be started. Therefore, if we chose "5" for the section delimiter, map A in Figure 27 would result, namely one big rectangle, since all the adjacent lines differ by not more than 5. However, if "3" is chosen for the section delimiter, the map B in Figure 27 would result. The first rectangle consists of lines 1-3 which all differ less than "3", while line number 4 differs from line number 3 by more than "3." Line number 4 also differs from line number 5 by more than "3." Therefore line 5 again starts a new rectangle, making it 3 rectangles altogether.

```
-----------------------------------------
| | | | |X| | | | | | |X| | | | | | | | | = 8 units long
-----------------------------------------
| | | | | |X| | | | |X| | | |X| | | | | | = 10
-----------------------------------------
| | | | | | | | |X| | | | | | | |X| | | | = 9
-----------------------------------------
| | |X| |X| | | | |X| | | | |X|X| | | | | = 14
-----------------------------------------
| | | | |X| | | | | | | |X| | | | | | | | = 9
-----------------------------------------
| |X| | | | | | | | | |X| | | | | | | | | = 11
-----------------------------------------
```

Figure 26. Arbitrary Pattern.

```
-----------------------------------------
| | | | |X|X|X|X|X|X|X|X|X|X|X|X|X| | | |
-----------------------------------------
| | | | |X|X|X|X|X|X|X|X|X|X|X|X|X| | | |
-----------------------------------------
| | | | |X|X|X|X|X|X|X|X|X|X|X|X|X| | | |
-----------------------------------------
|   |X|X|X|X|X|X|X|X|X|X|X|X|X|X| | | | |
-----------------------------------------
| |X|X|X|X|X|X|X|X|X|X|X|X| | | | | | | |
-----------------------------------------
| |X|X|X|X|X|X|X|X|X|X|X|X| | | | | | | |
-----------------------------------------
```

Map A

```
-----------------------------------------
| |X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X| | | |
-----------------------------------------
| |X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X| | | |
-----------------------------------------
| |X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X| | | |
-----------------------------------------
| |X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X| | | |
-----------------------------------------
| |X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X| | | |
-----------------------------------------
| |X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X| | | |
-----------------------------------------
```

Map B

Figure 27. Alternate Interpretations of Fig. 26.

Now that the disecting procedure has been explained, let's go back to Figure 25 which is the coarse grid map of Figure 24. We chose now as section delimiter "6" and obtained Figure 28 as a result. Note the first rectangle is 6 units wide and 3 lines high despite the fact that none of the first 3 lines has more than 5 units. If we had chosen "5" as section delimiter, we would have obtained a rectangle 5 units wide.

However, choosing "6" as a section delimiter produced the map of Figure 28. Now we compute the aspect ratios (x/y) of the obtained 4 rectangles, which are 1.50, 6.00, 1.60, and 4.67.

In order to make things less ambiguous we exchange x and y and go through the same procedure. This time we obtain only 3 rectangles, namely 2.00, 1.31, 1.33. Now we have a string of 8 numbers which we compare with the string of numbers which are stored for known pattern. We may require that at least 6 of the 8 numbers agree with the stored string to declare it a match.

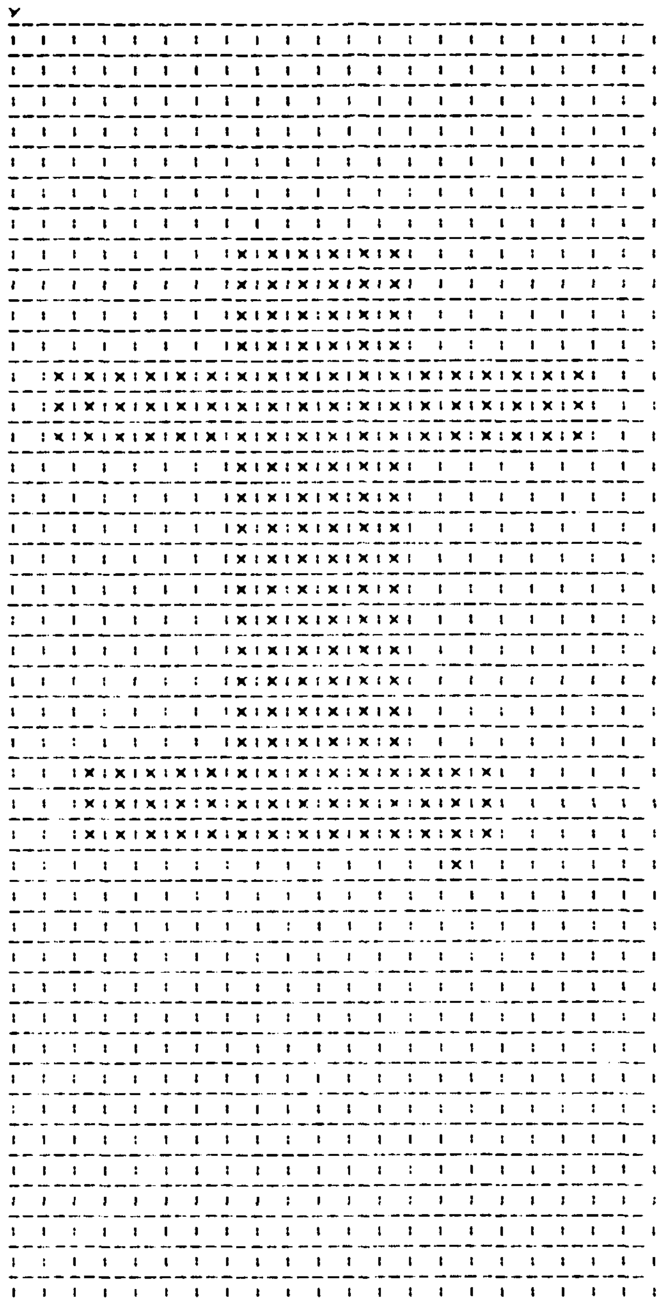


Figure 28. Final Coarse Map.

9. PERFORMANCE OF THE RECOGNITION PROGRAM

The performance of the above described recognition program was tested first with synthetic data and then with an actually acquired image. The shape used for the synthetic data is shown in Figure 29. It is a binary image of an airplane-like structure. The print-out "O" indicating unilluminated detectors was suppressed for the sake of clarity.

To these data some noise was added inside the pattern, which may simulate damaged detectors or underexposed detectors. The pattern with noise is shown in Figure 30. The program was able to recognize the pattern. Considering the way the recognition scheme works, this is not surprising. Since it checks for boundaries only, in effect, it converts everything to a shadowgraph. Missing elements inside a pattern are of no consequence.

Therefore, now noise was added to the outside of the pattern, leaving the pattern for the time being alone. This can be seen in Figure 31. Again, the system was able to recognize the pattern. This noise may simulate either detector noise or background illumination. If detector noise is simulated the situation is more favorable. The system, of course, "knows" where the footprints are. Therefore, to accept reports from detectors under void spaces would be only meaningful if the neighboring footprint had all 3 x 3 detectors illuminated. If this is not the case, signals coming from detectors under void spaces should be ignored. As far as signals in the footprints them

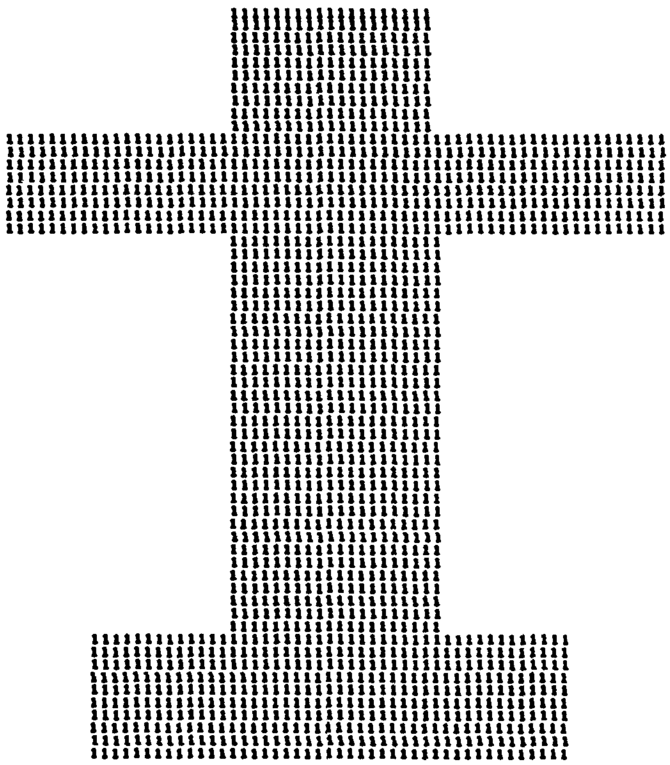


Figure 29. Synthetic Data.

selves are concerned, the number of "1" to be present can be set by the operator. However, there is also the side condition that irregardless of how many "1" are required the center detector of the footprint has to be one of the required "1."

A setting of 5 seems to be a reasonable choice. Therefore, scanning Figure 31 for a "1" which is surrounded by at least 4 other "1", it can be seen that there are only a few candidates. For these the additional condition that they are indeed the center of a footprint has to be fulfilled before a pixel is generated. This reduces the number of candidates even more. Therefore, it is not surprising that the system was able to recognize the pattern.

However, if the noise in Figure 31 was random background fluctuation rather than detector noise, the centers of the footprints would be preferably illuminated, since it is a real signal which is received. The system would have to treat these pixels as a part of the pattern, and, of course, could not recognize it. If a situation like this exists, a cure can be found by requiring at least 3 pixels per line (instead of one, as described above) to form a line belonging to a rectangle. This makes the system less sensitive but less prone to not recognize a known pattern. The sensitivity can be restored to some degree by requiring only four "1" instead of the 5 or 6 as done above.

Both types of situations, namely as shown in Figure 30 and 31, are superimposed in Figure 32. The target is now already marginal. Of course, the system will recognize it for the reasons explained already, since nothing has changed. Figure 33, however, is too noisy for the system to recognize, while the human system still recognizes albeit only if it knows what to look for.

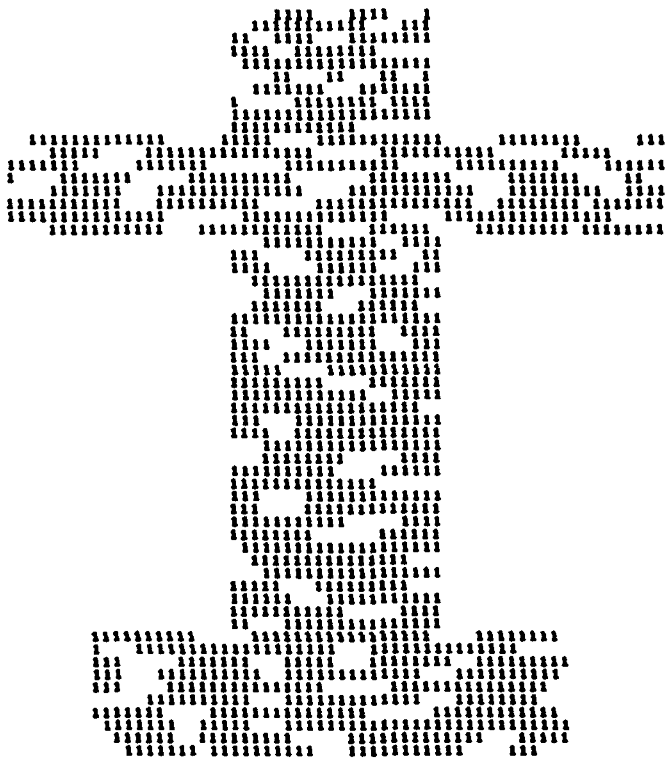


Figure 30. Noise Added to Fig. 29.

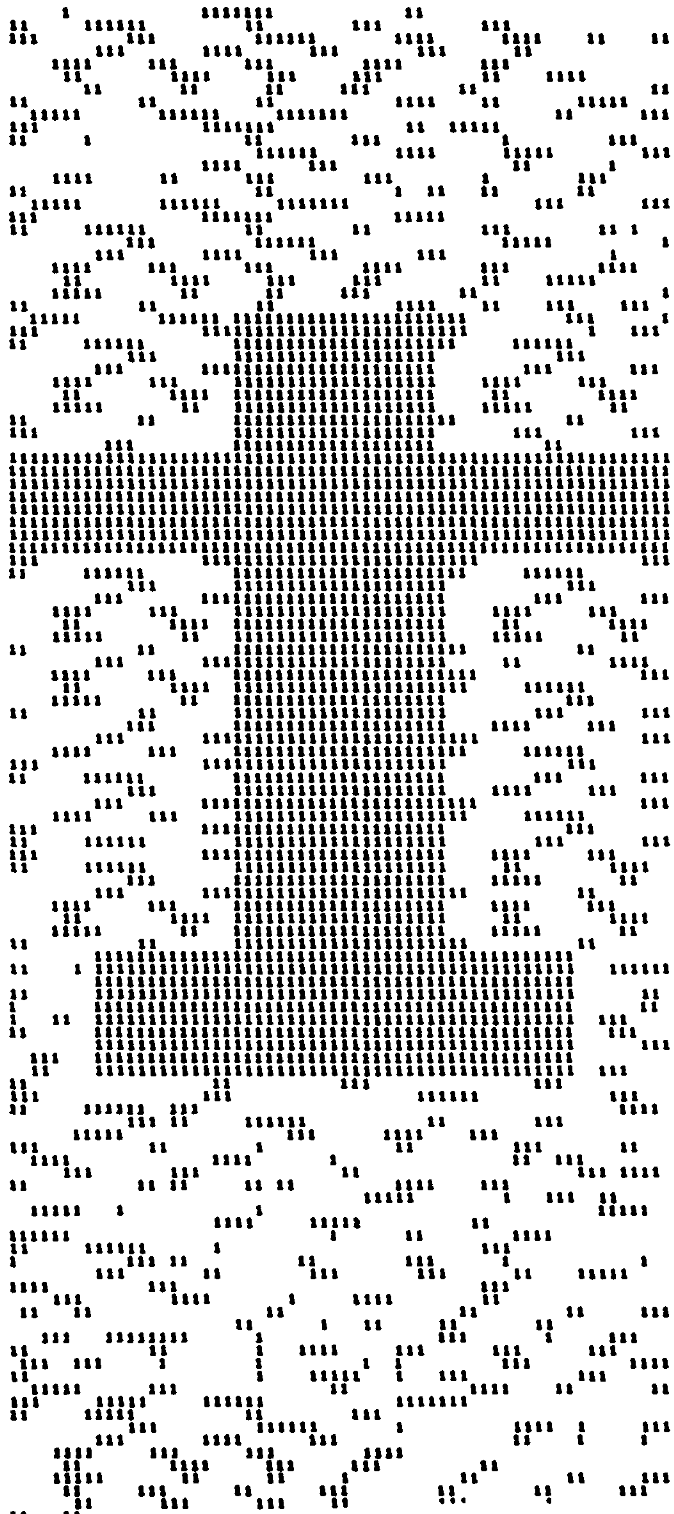


Figure 31. Outside Noise Added.

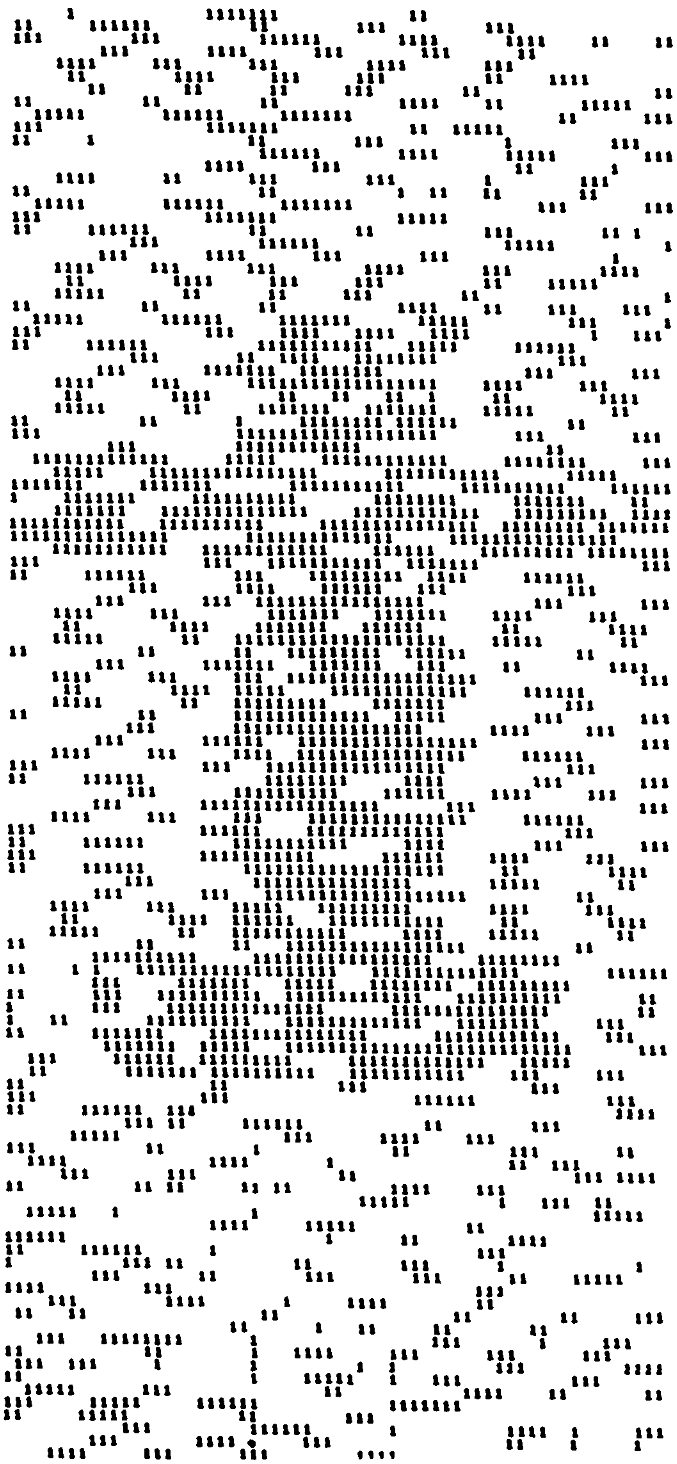


Figure 32. Combination of Fig. 30 and Fig. 31.

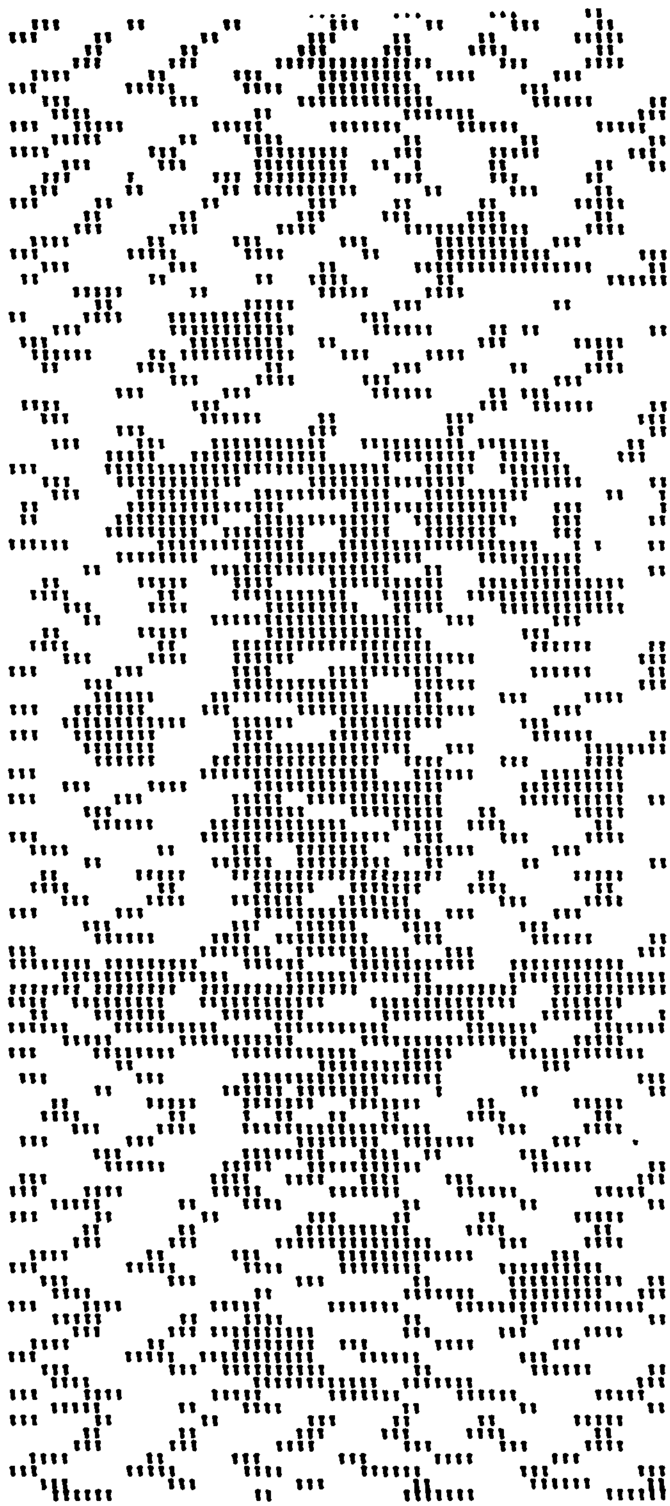


Figure 33. Noise Too Excessive for Recognition.

The recognition system was next employed to work on data taken by the experimental device. Figure 34 shows the binary image of an airplane-like structure as produced by the experimental device. The following sequence of figures shows first an unsuccessful attempt to recognize the acquired shape and then a successful one. The difference between the two is the selection of the value of the section delimiter.

The reduction of Figure 34 into footprints is shown in Figure 35. It was obtained by requiring at least 7 detectors to be illuminated in each footprint. Those which qualified were artificially filled with 9 binary "1." The coarse map derived from Figure 35 is shown in Figure 36. Then the section delimiter was set to "5" which produced the set of rectangles shown in Figure 37. The system was not successful in recognizing this set as a known pattern.

Resetting the section delimiter to "7" produces a different set of rectangles which is shown in Figure 38. The system recognized this shape as an airplane.

Since there is such a stringent limitation in the number of pixels available the system is very sensitive to rotation of the object. The recognition procedure has to be improved to allow an acquired pattern to be rotated until recognition is achieved.

```
ATFILE: PLANE.DAT
PABFILE: PLANE.PAB
To analyze a previously created [ ].PAB file, enter '1'
To analyze a new [ ].DAT file, enter '2'
1
reading in the data...

Would you like to see the data set?--'Y'
Y
```

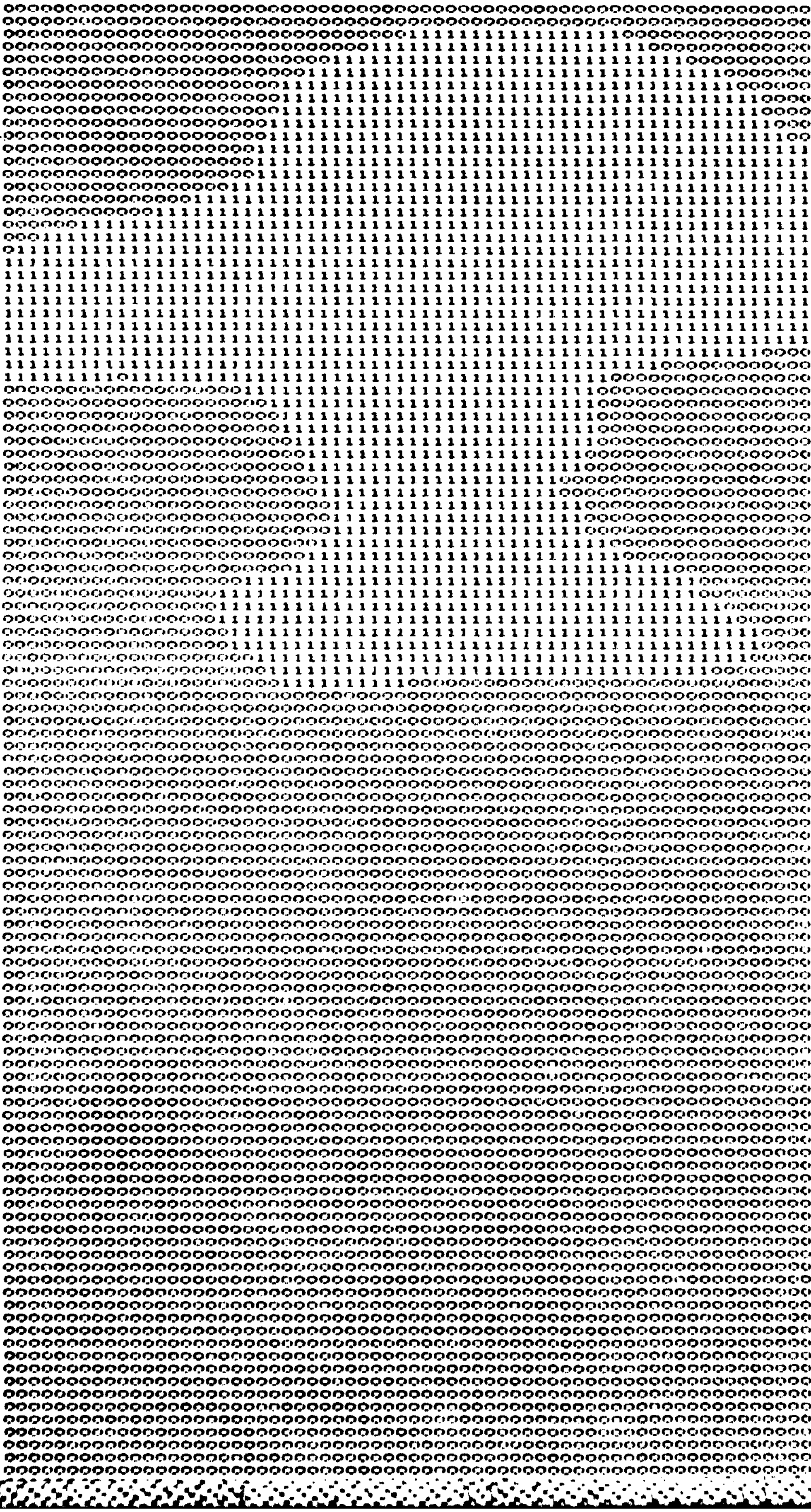


Figure 34. Airplane-like Structure as Acquired by MAO Device.

```
To attempt recognition with a series of toggle and threshold values, enter '1'
To attempt recognition with a single combination of these values, enter '2'
2
Value for pixel on/off toggle?--(from 1 to 9)
7
Value for sectional divider?--(from 1 to 21)
5
Would you like to see this eyelet pattern?-'Y'
Y
```

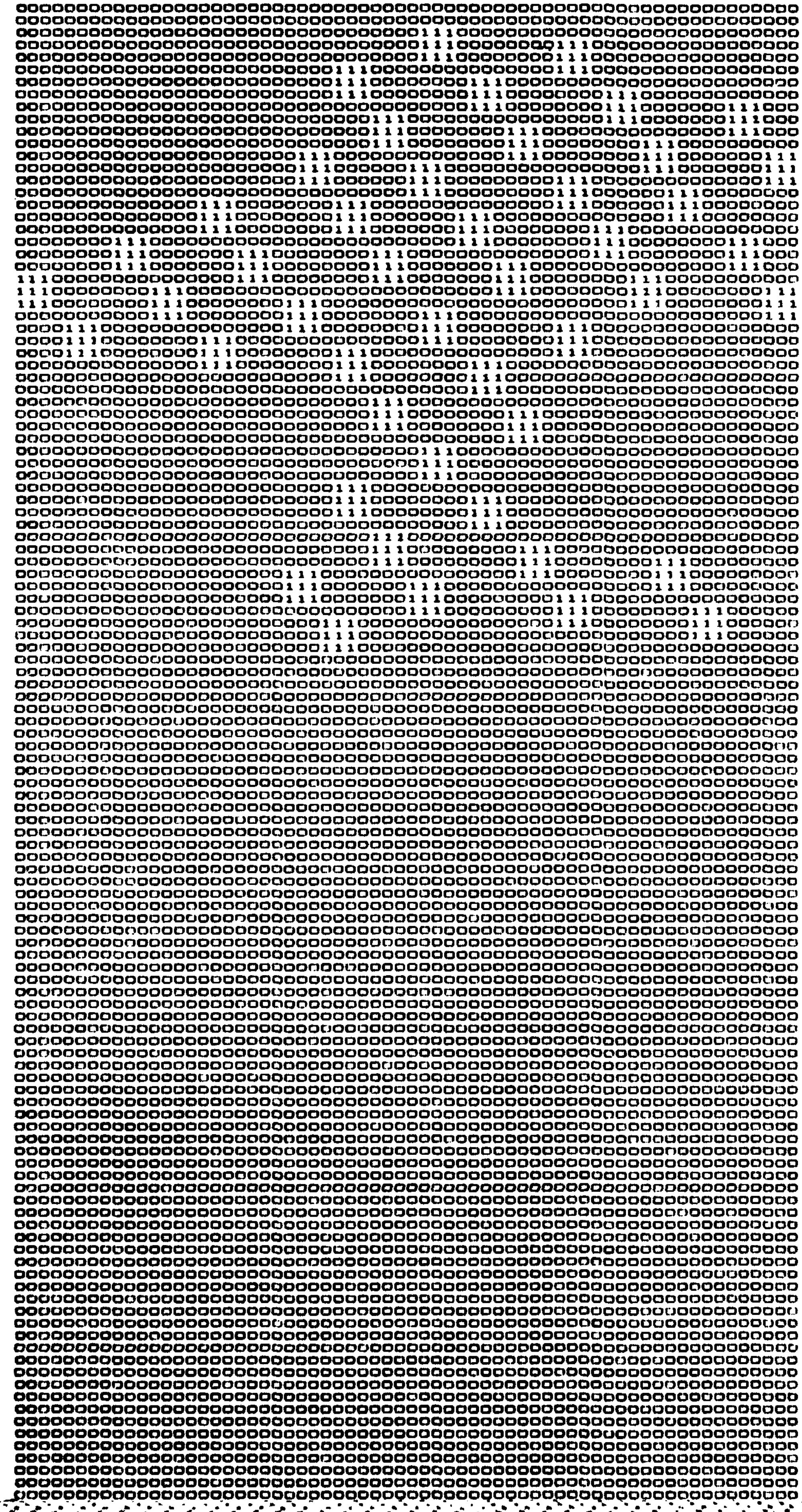


Figure 35. Reduction of Fig. 34 to Footprints.

Would you like to see this coarse square map?-
Y

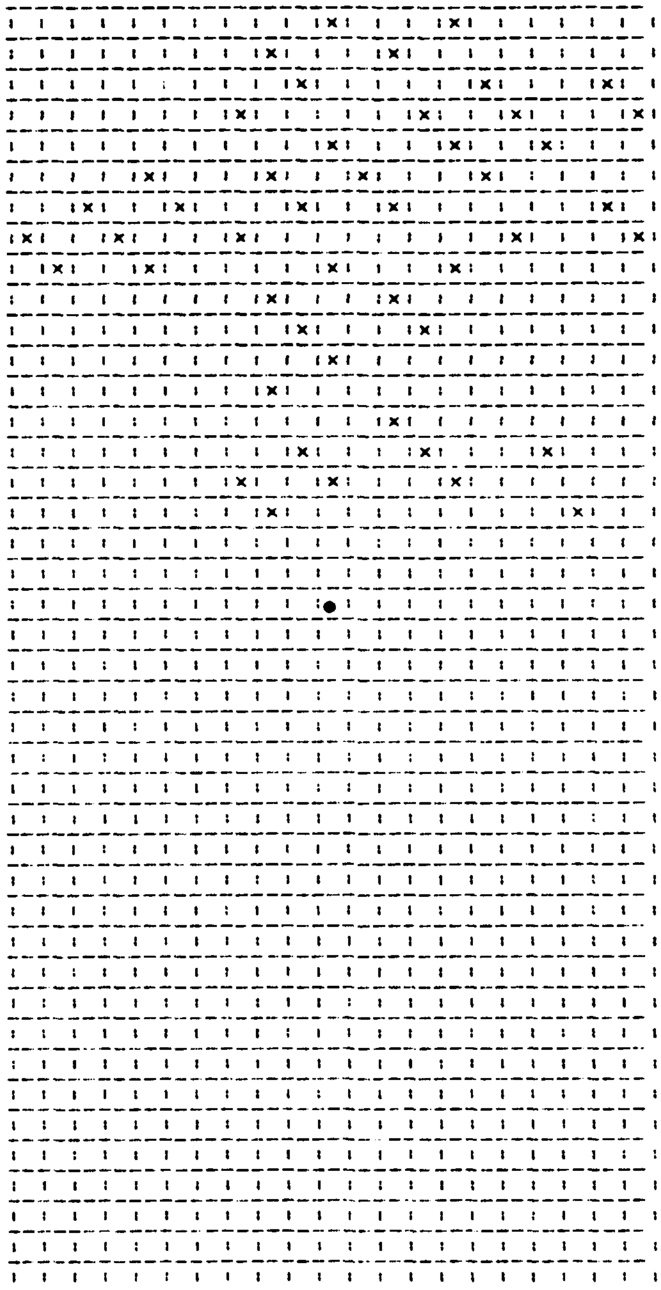


Figure 36. Coarse Map.

```
Analysis at pixel on/off toggle = 7
and sectional divider =           5
The X-axis features generated are:
     3.50        7.00        7.00       10.50       14.00        1.80        4.00
The Y-axis features generated are:
     0.71        1.42        3.00
Would you like to see the smoothed pattern?--'Y'
Y
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X|X| | | | | | |
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X|X| | | | | | |
-------------------------------------------
| | | | | | | |X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
| | | | | | | |X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
| | | | |X|X|X|X|X|X|X|X|X|X|X|X|X| | | | |
-------------------------------------------
| | | | |X|X|X|X|X|X|X|X|X|X|X|X|X| | | | |
-------------------------------------------
|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
| |X|X|X|X|X|X|X|X|X|X|X|X|X|X| | | | | | |
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X| | | | | | | |
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X| | | | | | | |
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X| | | | | | | |
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X| | | | | | | |
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X| | | | | | | |
-------------------------------------------
| | | | | | | |X|X|X|X|X|X|X|X|X|X|X|X| | |
-------------------------------------------
| | | | | | | |X|X|X|X|X|X|X|X|X|X|X|X| | |
-------------------------------------------
| | | | | | | |X|X|X|X|X|X|X|X|X|X|X|X| | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
```

Figure 37. Rectangles Produced from Fig. 36.

```
Analysis at pixel on/off toggle = 7
and sectional divider =          7
The X-axis features generated are:
     2.63      14.00      1.20      4.00
The Y-axis features generated are:
     1.29      1.42      4.00
At pixel on/off toggle = 7 and divider = 7, the pattern is a type 1 plane.
Would you like to see the smoothed pattern?--'Y'
Y
-------------------------------------------
|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|X|
-------------------------------------------
| |X|X|X|X|X|X|X|X|X|X|X|X|X|X| | | | | | |
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X| | | | | | | |
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X| | | | | | | |
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X| | | | | | | |
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X| | | | | | | |
-------------------------------------------
| | | | | | | | |X|X|X|X|X|X| | | | | | | |
-------------------------------------------
| | | | | | | |X|X|X|X|X|X|X|X|X|X|X|X| | |
-------------------------------------------
| | | | | | | |X|X|X|X|X|X|X|X|X|X|X|X| | |
-------------------------------------------
| | | | | | | |X|X|X|X|X|X|X|X|X|X|X|X| | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
| | | | | | | | | | | | | | | | | | | | | |
-------------------------------------------
```

Fig. 38. Rectangles Produced by Section Delimiter = 7.

10. CONCLUSIONS AND RECOMMENDATIONS

There are basic differences between MAO (multiaperture optics) and SLO (single lens optics) as well as gradual ones. Certainly the entrance aperture of the eyelets is smaller than in the case of SLO which is a gradual difference. In the first approximation one would say this causes a reduced resolving power for MAO. While this is a correct conclusion, the resolving power of (apposition) MAO is actually determined by the number of eyelets rather than the eyelet diameter, which is a basic difference between MAO and SLO.

Therefore the goal should be to use as many eyelets as possible. However, this distributes the available photon flux over larger and larger detector areas, which limits the achievable signal to noise ratio. For this reason even nature limits the number of eyelets used. The entrance aperture of individual eyelets used by nature is still between 100 and 500 times the wavelength of light instead of one times which would be a theoretical limit. In an artificial device one would limit the number of eyelets even more.

To make good for the limited resolution of the so obtained system, an attempt should be made to extract more information than just the existence of one pixel from the footprint of each eyelet.

In the system described in this report, we do this only in a primitive way, namely requiring that one of the 9 detectors producing a signal within one given footprint has to be the center detector. In addition we require also the presence of intensity on a certain number of other detectors within the same footprint. The latter amounts to

thresholding, although at a later stage of development this may be used to construct a gray scale. The important feature, however, is requirement for the presence of the center detector. Since the system "knows" which one the center detect is, and since this detector has a non-overlapping FOV, the combination of center detector and outer detector allows deduction of additional information. An example is the case where an edge goes through the middle of an eyelet. The outer detector will tell in which direction the illuminated part is, while the presence of the center detector tells that the edge goes through the FOV of the eyelet (presumably near the center). Therefore, this gives a better resolution than should be expected.

A check for illuminated detectors under void spaces, where the neighboring footprints do not have a center detector illuminated, will give an indication of the noise present.

Checking for coincidences between detectors having overlapping FOVs will help improve the signal to noise ratio.

All these features still need to be incorporated in the image evaluation system.

Also, the problem of rotating the image after each unsuccessful recognition attempt still needs to be incorporated.

However, the present effort shows that a MAO device which can recognize simple patterns using a minimum of computational effort can indeed be built as an inexpensive mass product as well as a physically small device.

END
FILMED

6-86

DTIC